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HIGHWAY RESEARCH REPORT

FRACTURE TOUGHNESS OF HIGH STRENGTH BRIDGE STEELS

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FINAL REPORT

June, 1974

STATE OF CALIFORNIA BUSINESS AND TRANSPORTATION AGENCY DEPARTMENT OF TRANSPORTATION DIVISION OF HIGHWAYS	TRANSPORTATION LABORATORY RESEARCH REPORT CA-DOT-TL-6593-1-74-20

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16. ABSTRACT

The static fracture toughness (K_{IC}) characteristics of 2 to 2-1/4 inch thick, A514/A517 ($\sigma ys \approx 100$ ksi) steel is investigated using the compact tension (CT) test, the standard Charpy V-notch (CVN) test, and the precracked Charpy impact (PCI) test. Purported correlations relating K_{IC} values to CVN values are evaluated and a new correlation between K_{IC} to PCI values is derived. Also investigated is the practicality of a fracture control program which attempts to guarantee toughness values (in terms of Charpy impact energy) sufficient to insure a "thru-thickness yielding" failure mode, thereby eliminating the danger of sub-yield level brittle fracturing. The validity of using CVN and PCI notch ductility (lateral expansion) measurements to indicate fracture toughness is discussed.

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RONALD REAGAN, Governor

DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
TRANSPORTATION LABORATORY
5900 FOLSOM BLVD., SACRAMENTO 95819

June 1974

Trans Lab No. 646593

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a final research report titled:

FRACTURE TOUGHNESS

OF

HIGH STRENGTH BRIDGE STEELS

Principal Investigator
Roger D. Smith

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Under the Supervision of
Eric F. Nordlin

Very truly yours,

JOHN L. BEATON
Chief, Transportation Laboratory

ACKNOWLEDGEMENT

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Floyd E. Martin Joseph E. Wilson Ervin M. Eisenbraun	Precision machining of test specimens and testing hardward
Richard L. Johnson Delmar M. Gans William A. Ng	Fabrication and operation of high sensitivity load-displacement recording equipment

They also wish to thank Carl E. Hartbower and Walt G. Reuter of the Aerojet General Corporation for their cooperation and assistance.

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I. INTRODUCTION

In recent years, several instances (1) (one in California) of failure in steel at stresses well below yield strength level have suggested that an abrupt failure process, quite unlike the slower and more conventional yielding process, might well be controlling structural performance. This unusual form of structural failure was characterized by an absence of plastic strain evidence and a flat planar fracture face extending from an apparent flaw of some kind. For this reason the failure mechanism was appropriately termed "brittle fracture". "Fracture toughness" is simply a measurement of a materials resistance to "brittle fracture" in the presence of a flaw or crack.

The brittle fracturing of a girder flange in the Bryte Bend Bridge near Sacramento was the impetus for this research project. Although the phenomenon of brittle fracture in steels has been known for some time, it has only recently become a primary concern in highway bridge construction. Several explanations are offered for this as follows:

1. Welding, the steel joining method most likely to result in the stresses, flaw types and crack growth rates necessary for brittle fracture, is a relatively new bridge construction method. Early welded structures are only now reaching the "ripe" age where fatigue, stress corrosion and other metallurgical mechanisms may have had time to grow flaws approaching the size required to initiate brittle fracture.

2. The crack growth rate in bridge steels is primarily dependent on and varies directly with the magnitude of stress fluctuations. However, studies indicate that the stress fluctuation range (due to live loads, etc.) is very small in most highway bridges. Hence, most of these bridges are blessed with long lives and are only now beginning to be in danger of containing fatigue cracks large enough to initiate brittle failure.

3. Higher strength weldable steels are now being used in bridge construction. These steels are inherently more susceptible to brittle fracture than their lower strength counterparts unless they have greater toughness. This situation is aggravated by the use of higher design stresses consistent with the increased strength levels of these steels. These higher stresses reduce the minimum crack size for brittle fracture unless the toughness of the steel is increased as much or more than the increase in applied stress. This smaller crack size for brittle fracture means that the time required to grow a fatigue crack to that critical size is shorter. Hence, the life expectancy of new high strength steel structures is of greater concern than for low strength grades.

The general objective of this study was to develop a meaningful toughness performance criteria and test method, which would facilitate the safe controlled use of high strength bridge steels, thereby allowing the designer to provide longer, more efficient spans with reduced structure depths, improved aesthetic features, and equivalent theoretical life expectancies.

This study investigated seven heats of ASTM A514/A517 steel representing two producers, United States Steel and Lukens Steel. Sketches of typical test specimens used are shown in Figure 1. This grade of high strength (σy 100 ksi) bridge steel was chosen because its demonstrated susceptibility to brittle fracturing has limited the use of this otherwise popular material. As explained earlier, the susceptibility to brittle fracture inceases with yield strength unless the toughness of the steel is increased at the same rate the yield strength increases. Unfortunately, this high level of toughness generally has not been realized in A514/A517 steels tested by the State of California.

The specific objectives of this project were:

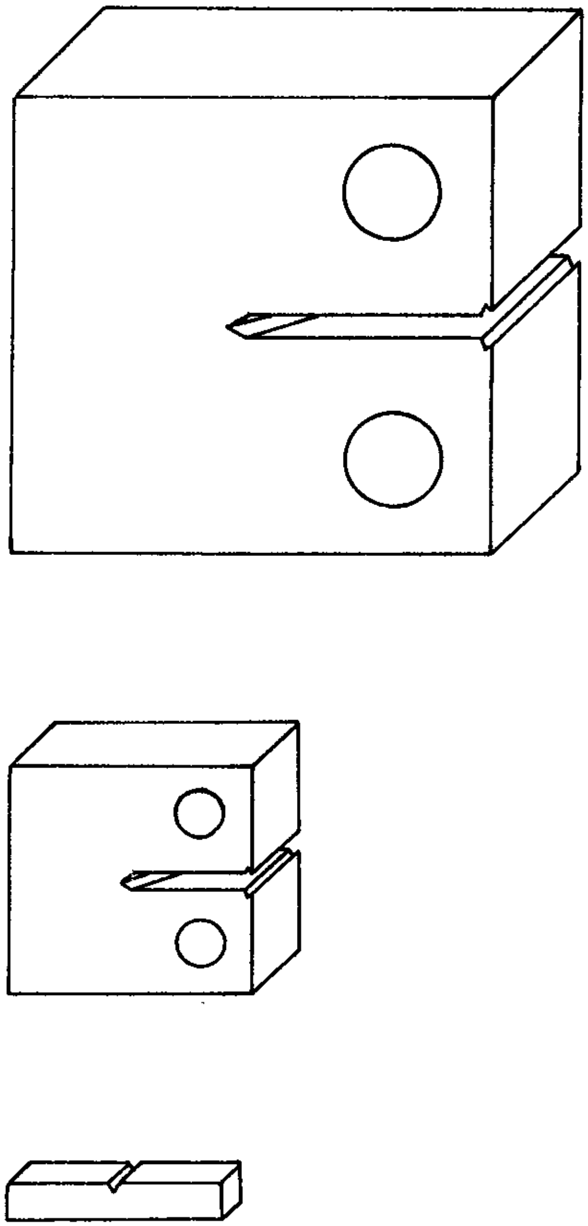
1. To verify the relationship between precracked Charpy impact transition temperature and the inflection in the plot of K_{IC} (compact tension test) versus test temperature as reported by Barsom and Rolfe (3).

2. To verify empirical relationships between Charpy impact test results and plane strain fracture toughness (K_{IC}) as reported by Barsom and Rolfe (4).

3. To evaluate the concept of "thru-thickness yielding" (5)(6) as the basis for steel toughness requirements.

Fracture toughness testing for this investigation was performed under contract No. 19-1217 by the Aerojet General Corporation of Sacramento, California. Principal investigators for Aerojet were Carl E. Hartbower and Walter G. Reuter. Their report is attached as an Appendix to this report.

This project also accomplished the training of Transportation Laboratory personnel in the field of fracture toughness testing according to the ASTM E399 "compact tension" test method. All necessary test equipment, including loading devices, crack opening displacement gauges, and load-displacement plotting equipment was made in the Transportation Laboratory Machine Shop, thus giving this agency full compact tension testing capabilities.



a. 2" K_{Ic} Specimen

(Compact Tension type)

b. 1" K_{Ic} Specimen

(Compact Tension type)

c. Charpy Specimen

FIGURE 1

TEST SPECIMENS USED IN THIS STUDY
(approx. 1/2 scale)

II. CONCLUSIONS

From this research it is concluded that:

(1) A correlation between the lower limits of the brittle-ductile fracture transition temperature ranges of the precracked Charpy impact (PCI) test and the static compact tension test does not exist for the seven heats of ASTM A514 or A517 steel investigated.

(2) The toughness of these steels was too great at temperatures above the upper limit of the brittle-ductile fracture transition temperature range (upper shelf temperatures) to be validly measured with 2"-thick compact tension specimens from the material available for testing. Hence, there was no opportunity to verify the following empirical relation developed by Barsom and Rolfe (4) for this temperature range;

$$\left(\frac{K_{Ic}}{\sigma y}\right)^2 = \frac{5}{\sigma y}\left(CVN - \frac{\sigma y}{20}\right)$$

where: K_{Ic} = critical plane strain fracture toughness (ksi$\sqrt{in}$)

σy = yield strength (ksi)

CVN = Charpy V-notch impact energy (ft-lbs).

(3) The critical static plane strain fracture toughness of these seven steels at the lower half of the Charpy V-notch brittle-ductile fracture transition temperature range could be estimated from Charpy V-notch tests by using the following correlation developed by Barsom and Rolfe (4);

$$K_{Ic}^2 = (2E)\ CVN^{3/2},$$

where: K_{Ic} = psi$\sqrt{in}$

E = psi

CVN = ft-lbs (impact).

(4) Estimates of the critical static plane strain fracture toughness derived by applying the Corten-Sailors expression (7),

$$K_{Ic} = 15.5\,(CVN)^{1/2},$$

where: K_{Ic} = ksi $\sqrt{in}$

CVN = ft-lbs (impact),

were more conservative than those by the Barsom-Rolfe correlation for the seven steels tested.

(5) Using the expression developed by Hartbower and Reuter in this study,

$$K_{Ic} = [18E\ PCI]^{1/2},$$

where: K_{Ic} = psi

E = psi

PCI = ft-lbs,

with the precracked Charpy impact test data provided a more accurate estimate of the critical static plane strain fracture toughness than the conventional Charpy V-notch impact test data did with either the Barsom-Rolfe or the Corten-Sailors correlations.

(6) For the seven steels examined in this study, the mils of lateral expansion in a broken PCI specimen numerically approximates the energy absorbed (ft-lbs) in breaking that specimen.

(7) Only two of the seven steels tested demonstrated sufficient toughness to meet the "thru-thickness yielding" criterion for minimum toughness. This criterion, expressed as:

$$K_{Ic} = \sigma y \sqrt{t},$$

where: K_{Ic} = ksi $\sqrt{in}$

σy = ksi

t = thickness - inches,

is based on work by Hahn and Rosenfield (6) which indicated that in material meeting this criteria, thru-thickness yielding provided enough stress relaxation of the tips of cracks to prevent brittle fracturing.

(8) The reported (4) shift (approximately 60°F) in brittle-ductile fracture transition temperature between static and dynamic tests could not be verified for the seven heats of A514/A517 steel examined in this study.

III. RECOMMENDATIONS

1. That Rolfe's CVN-K_{Ic} transition temperature correlation (Equation (4)) be used within its limits, to enable estimation of K_{Ic} values from Charpy V-notch test results.

2. That the precracked (rather than V-notch) Charpy impact test be used as the routine test for toughness estimation.

3. That the PCI-K_{Ic} transition zone correlation(Equation (7)) developed by Hartbower and Reuter from this testing program, be used to estimate static K_{Ic} values from PCI energy absorption.

4. That for specification purposes,the lateral expansion (mils) and energy absorption (ft-lbs) in the PCI test be considered numerically equal for the type of quenched and tempered steels (100 to 110 ksi yield strength) tested in this investigation.

5. That PCI lateral expansion (rather than energy absorption) measurements form the basis for future toughness check testing requirements.

IV. IMPLEMENTATION

The performance of this research study has contributed greatly to the knowledge of fracture mechanics possessed by the personnel of the Transportation Laboratory. More specifically, the fracture behavior of ASTM grade A514/A517 steel, a popular highway bridge building material, has been better defined in terms of simple test variables. The use of this steel is desirable from the standpoint of its high strength-to-weight ratio, considering that its yield strength is more than twice that of conventional bridge steels such as A36 or A441.

Knowledge gained from this study will have several applications:

1) the evaluation of proposed toughness specifications for A514/A517 steel

2) the evaluation of proposed test methods for measuring fracture toughness

3) the development of an overall fracture control program which combines a realistic fracture toughness testing program with the judicious use of nondestructive inspection in shop and field.

At present, the fracture toughness requirements for A514/A517 steel in bridges, as dictated by the Federal Highway Administration (FHWA), are not in line with the findings of this study. The FHWA requirements, expressed in terms of Charpy impact energy values, are based on the findings of John M. Barsom (18), a U.S. Steel Co. researcher heading the AISI Project 168, "Toughness Criteria for Structural Steels."

The findings of this study are in disagreement with AISI project's findings in two primary areas:

1. No consistent temperature shift between the static and dynamic Charpy energy vs. temperature curves was evident in this study.

2. The use of the precracked (rather than the V-notch) Charpy specimen was found to be a more realistic indicator of fracture toughness in this study.

These findings will therefore be valuable in future attempts to improve the FHWA toughness (Charpy) requirements and the attendant level of protection against brittle fracture in A514/A517 steels. But before a realistic specification can be developed, research must be conducted towards determining the effective strain rate at the tip of an active flaw (i.e., the strain rate that controls the failure process). Test requirements could then be expressed in terms of fracture toughness values determined at the strain (loading) rate commensurate with the actual service condition.

V. TECHNICAL DISCUSSION

1. History

Origin 15 ft-lbs @ 40°

Real concern for the brittle fracture susceptibility of steels arose primarily from the ship fracture crisis (12)(17) during and subsequent to World War II. Of the 4,694 ships involved, 1,200 (about 25%) cracked in some brittle manner. Nineteen ships abruptly broke in two and 250 failed to a degree that required their removal from service. It was found that ship fractures initiated in steels with Charpy V-notch impacts averaging about 7 ft-lbs at failure temperature and arrested in steels with Charpy impacts averaging from 14 to 16 ft-lbs (depending on analysis) at failure temperature (12). Thus a Charpy V-notch impact requirement of 10 ft-lbs (17) at the lowest anticipated use temperature or its equivalent; 15 ft-lbs at 20°F above the lowest anticipated use temperature, provided a way to discriminate between brittle and "safe" ship plate.

Later work (17) by the NBS Statistical Engineering Section related chemical composition to 15 ft-lb Charpy transition temperatures statistically to an accuracy of 80% within $\pm$ 20°F using the following expression:

$$T_{15}=83+316(\%C)-111(\%Mn)+459(\%P)-240(\%Si)-8.7(\text{Grain Size No.}) \quad \text{Eq. (1)}$$

where: C = carbon
Mn = manganese
P = phosphorus
Si = silicon
T_{15} = 15 ft-lb CVN transition temperature.

Apparently, based in part on this expression, the specified compositions for ship plate were redesigned so that about 94% of the heats would have 15 ft-lb temperatures at least as low as the T_{15}=62° displayed by the best fracture source ship plate tested up to that time. Since the expression was only accurate to $\pm$ 20°F, compositions had to be based on T_{15} of approximately 20° lower than 62° or T_{15}=40°F. This appears to be a possible origin of the 15 ft-lb at 40°F requirement that so many have sought to justify placing in new bridge steel specifications.

In ship plate these requirements were apparently expected to provide brittle fracture arrest capability down to 40°F in all cases and protection against brittle fracture initiation down to the expected maximum 10 ft-lb temperature of 20° to 30°F. This was below the failure temperatures of about 90% of the heavy weather ship casualties.

$$K_{Ic} = \sigma y \sqrt{t}, \quad \text{where} \quad \begin{aligned} \sigma y &= \text{ksi} \\ t &= \text{in} \\ K_{Ic} &= \text{ksi}\sqrt{\text{in.}} \end{aligned} \qquad \text{Eq. (4)}$$

This was called the "thru-thickness yield" criterion. In 1969 Rolfe, et al, (18) presented an empirical relation between static plane strain toughness and Charpy V-notch impact energies for steels tested at temperatures above the Charpy brittle-ductile fracture transition temperature range. This was

$$\left(\frac{K_{Ic}}{\sigma y}\right)^2 = \frac{5}{\sigma y}\left(CVN - \frac{\sigma y}{20}\right), \quad \text{where} \quad \begin{aligned} \sigma y &= \text{ksi} \\ CVN &= \text{ft-lbs} \\ K_{Ic} &= \text{ksi}\sqrt{\text{in.}} \end{aligned} \qquad (5)$$

This expression was combined with the Hahn-Rosenfield thru-thickness yield criteron to derive a minimum Charpy V-notch requirement for assurance against brittle fracture that was based on both yield strength and section thickness and expressed as follows:

$$CVN = \frac{\sigma y}{5}(t+0.25), \quad \text{where} \quad \begin{aligned} t &= \text{in} \\ \sigma y &= \text{ksi} \\ CVN &= \text{ft-lbs.} \end{aligned} \qquad \text{Eq. (6)}$$

Justifying a 15 mil CVN Specification

In 1970 Gross (16) compared the upper shelf CVN requirements of Equation (6) with those imposed by the 15 mil expansion criterion. This comparison, shown in Figure 2, seems to demonstrate that a lateral expansion of 15 mils in a Charpy test provides material that is tough enough to meet the Hahn and Rosenfield requirement for upper shelf thru-thickness yielding in steel up to about 1" thick. (Only 1" plate was tested.) This would seem to limit the application of the 15 mil CVN requirement to steel less than 1" thick. However, in 1970 Barsom and Rolfe (4) showed that there was an apparent down shift in brittle-ductile fractive transition temperatures with decreasing strain rates. Consequently, the toughness of a steel at the low loading rates thought to be encountered in most real applications was held to be much greater than the Charpy V-notch test indicated via the Equation (5) correlation. Later work performed by Barsom (20) seemed to confirm these conclusions (7). Hence, the CVN requirement established for 100 ksi yield quenched and tempered bridge steels 1" thick was accepted by AASHTO as an adequate requirement for these steels up to 2-1/2" thick. ASTM A517-72a similarly includes the 15 mil lateral expansion CVN requirement for steels up to 2-1/2" thick.

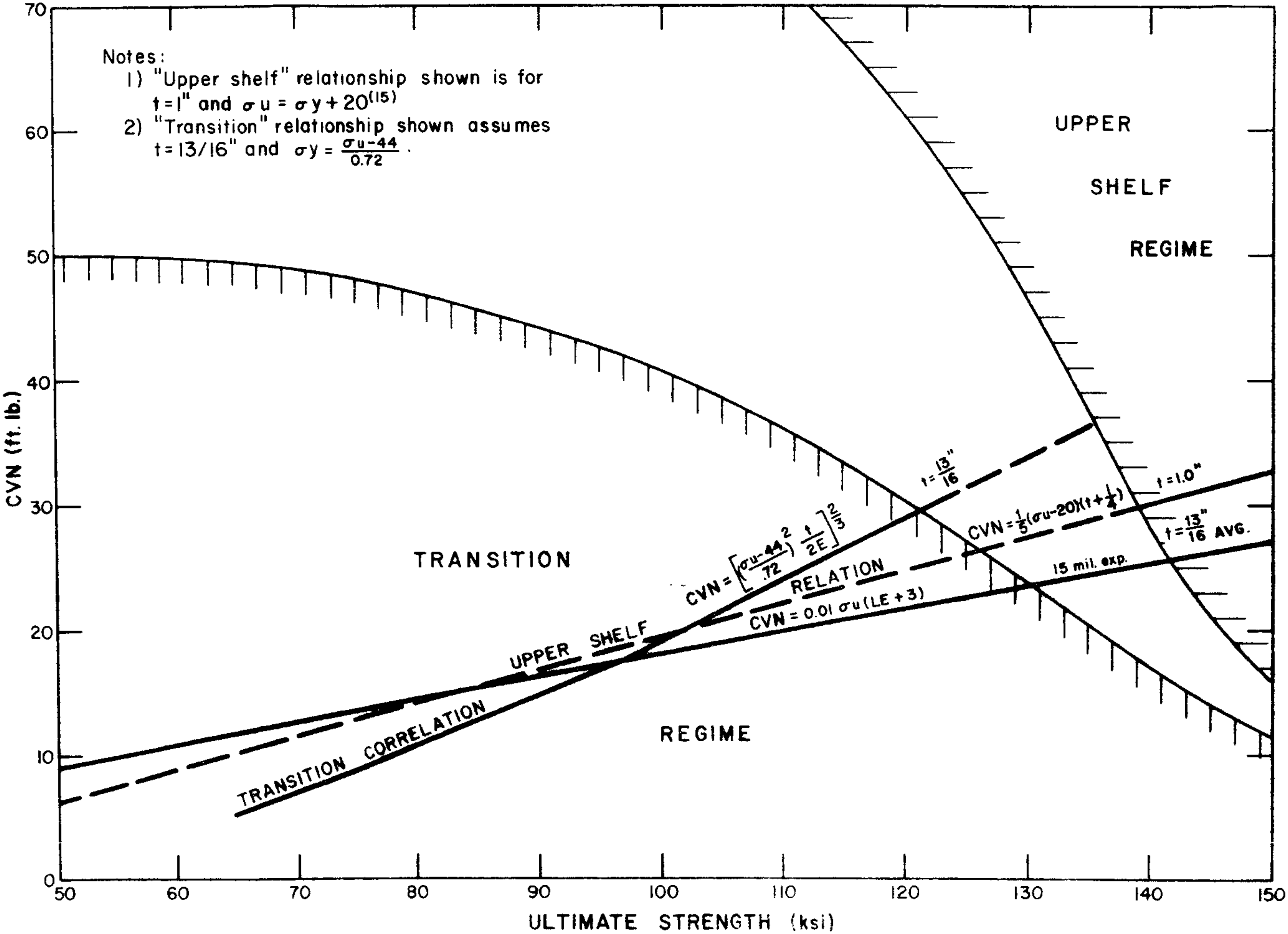


Fig. 2 COMPARISON OF POPULAR CHARPY IMPACT ENERGY CRITERIA

Origin and Significance 15 mil Lateral Expansion

Although the 15 ft-lb criterion provided some degree of protection against fracture in ship steels, its validity with respect to higher strength steels was questioned by many fracture experts. Some began investigating the relation between strength, energy, and the plastic increase in width of a broken Charpy V-notch specimen where the pendulum strikes it on the back side, opposite and behind the notch. This measurement, called the "lateral expansion" (LE), is approximately proportional to the energy absorbed in fracturing the specimen.

In 1958 work was published (11) showing that for a given measure of lateral expansion (LE) the Charpy energy increases linearly with the ultimate strength of the steel tested. The rate of increase shown by that work can be summarized by the following expressions:

$$LE = \left(\frac{100\ CVN}{\sigma u}\right) - 3, \qquad \text{Eq. (2)}$$

where: LE = mils
CVN = ft-lbs
σu = ultimate strength - ksi

or;

$$CVN = \frac{\sigma u(LE+3)}{100}. \qquad \text{Eq. (3)}$$

That work indicated that for the 60 ksi ultimate strength average of ship plate, a lateral expansion of 15 mils in a broken Charpy V-notch specimen corresponds to an 11 ft-lb fracture energy and provides a method of defining brittle-ductile transition temperature which is conservatively equivalent to the 10 ft-lbs criteria developed from ship plate. This work implied that a Charpy V-notch requirement of 15 mils minimum lateral expansion at minimum use temperature might be used independent of steel strength and thickness to provide an assurance against brittle fracture equivalent to that provided in the ship plate by the 10 ft-lb requirement.

The Problem of Thickness vs. CVN

Now another problem reappeared. As early as 1920 investigators had recognized an inverse variation of brittle fracture strength with cross-section or thickness (19). In 1967 Hahn and Rosenfield (6) proposed that the minimum toughness required in a steel plate to prevent brittle fracture increases with the square root of its thickness in accordance with the following expression:

The establishment of a single lateral expansion requirement for steels of various strengths and thicknesses was based on the hypothesis that energy absorption was the product of strength and ductility, and hence, ductility as measured by lateral expansion in steels of different strengths could be equated to different energy absorptions. The basic validity of this approach is questionable from the standpoint that no consideration is given to the higher toughness required of steels in service under conditions of greater geometrical constraint (i.e., thick sections, etc.).

Comments on Historical Findings

The work covered in this report did not confirm any systematic decrease in toughness with increasing strain rate that could be equated to a temperature shift. Possible reasons for this are discussed in the report. Hence, until more information is developed on this subject, the Charpy impact and other dynamic test requirements should continue to be based on the minimum anticipated use temperature. Testing at higher temperatures to account for strain rate differences should not be permitted.

An examination of Figure 2 suggests that if the CVN-σu relationship (Equation (6)) derived using the upper shelf correlation between K_{Ic} and CVN is correct, the 15 mil LE criteria will not provide the same degree of protection against brittle fracture as is provided by the use of Equation (6) for 1" plate. Also, for thicker plates, the inadequacy of the 15 mil LE criteria becomes more pronounced.

If instead of Rolfe's "upper shelf" relation, one uses the relation developed by Barsom and Rolfe (4) to relate "transition" temperature Charpy values to plane strain toughness,

$$\frac{K_{Ic}^{2}}{E} = 2(CVN)^{3/2}, \quad \text{where } K_{Ic} = \text{psi}\sqrt{\text{in}}, \; E = \text{psi}, \; CVN = \text{ft-lbs} \qquad \text{Eq. (7)}$$

and applies the Hahn-Rosenfield thru-thickness criteria (Equation (4)) to this expression one gets

$$CVN = \left(\frac{\sigma y^{2} t}{2E}\right)^{2/3}, \quad \text{where } CVN = \text{ft-lbs}, \; \sigma y = \text{psi}, \; t = \text{in}, \; E = \text{psi} \qquad \text{Eq. (8)}$$

When $\sigma y = \frac{\sigma u-44}{.72}$, where σy and σu = ksi Eq. (9)

is substituted in Equation (8) it becomes

$$CVN = \left[\left(\frac{\sigma u-44}{.72}\right)^2 \frac{t}{2E}\right]^{2/3}, \quad \text{where} \quad \begin{aligned} CVN &= \text{ft-lbs} \\ \sigma u &= \text{psi} \\ t &= \text{in.} \end{aligned} \qquad \text{Eq. (10)}$$

An examination of Figure 2 indicates that if the transition correlation between CVN and σu in Equation (10) is correct, then 15 mils lateral CVN expansion does not assure thru-thickness yielding in 13/16"* thick plates with ultimate strengths greater than 95 ksi. This seems to confirm the belief of some investigators that the 15 mil correlation only holds true for "lower strength" (i.e., C, C-Mn, C-Mn-Si, and low alloy) steels (13). Thus constant lateral expansion does not appear to assure equivalent resistance to brittle fracture with increasing strength even when thickness is held constant.

In the case of higher strength, quenched and tempered (Q & T) steels, such as grade A517, LE requirements must be customized for each strength and thickness of material. Hence we did not consider the 15 mil criterion valid for the group of steels studied herein.

The level of LE necessary is a subject of controversy, but the merits of the LE (as opposed to energy) measurement as a toughness indicator are recognized by the California Division of Highways and it may well form the basis for future toughness specifications.

2. Basic Fracture Concept

The Charpy test served as an empirical screening test for brittle steels, until the phenomenon of brittle fracture was able to be characterized through a relatively new science known as "fracture mechanics". Fracture mechanics defined a material's resistance to brittle fracture in the presence of a crack as its "fracture toughness", represented by the symbol "K". Because this approach is based on theory, it is possible to express fracture propensity in terms of stress, flaw size, and plate thickness - units meaningful to the designer. The basic fracture mechanics approach is discussed in the paragraphs that follows.

*The early ship plate investigation (12), upon which the 15 mil LE criteria is based, tested plate ranging in thickness from 1/2" to 1-1/2" and averaging 13/16". Hence, in Figure 2, t=13/16" was assumed in constructing the comparison curve based on transition zone thru-thickness yielding criteria.

For brittle fracture to occur, a flaw (crack) must initiate and grow to a critical size by such mechanisms as fatigue, stress corrosion or hydrogen embrittlement.

This critical crack size (2) is a function of the steel's toughness and the applied nominal* section stress. This relationship is expressed as follows:

$$K_{Ic} = C\sigma \sqrt{\pi a_c} \qquad \text{Eq. (11)}$$

where: K_{Ic} = critical plane strain fracture toughness (ksi $\sqrt{in}$)

σ = applied nominal stress (ksi)

a_c = critical flaw size (in)

C = constant defined by flaw geometry

When the critical crack size is exceeded, and the steel's critical fracture toughness is exceeded by the resulting crack tip stress intensity, the crack will abruptly propagate across the full section, constituting a brittle fracture.

Toughness is really a measure of the "constraint" in a crack tip plastic zone, or in other words, a measure of the resistance to thru-thickness (lateral) deformation at the crack tip. As a zone of material surrounding the crack tip stretches plastically, there should be an accompanying "necking" deformation in the thru-thickness direction. In an area of high constraint, this necking is not realized, and the mode of stress is termed "plane strain". Where constraint is low, thru-thickness "necking" occurs and a "plane stress" stress mode exists.

"Constraint" may be described as the inhibition of plastic flow due to stress triaxiality (16). Stress triaxiality is a state of three directional stress caused by the opposition to thru-toughness plastic flow by the elastic material which surrounds the plastic zone. In thicker plate, where the thru-thickness crack-front breadth and the attendant elastic zone are longer, the degree of flow inhibition is greater. Flow inhibition ultimately subjects the metal grains at the crack tip to abnormally high stresses for a relatively low applied load. In general then, toughness decreases with increasing thickness to a lower limiting value known as the "critical plane strain

*Where the crack is able to grow through the zone of high residual stress without fracturing.

fracture toughness (K_{Ic})". Popular methods of measuring K_{Ic} require test specimens which are thick enough to provide this maximum constraint. One of these methods, known as the "compact tension" test, is outlined in ASTM E399-72. But this method requires large specimens, costly machining, and a relatively complex test method. For these reasons various research efforts (4)(7) have attempted to correlate results from the simpler Charpy impact test (ASTM E23-72) to the actual K_{Ic} measurements (Figure 1). This would provide an indication of toughness using a relatively small, inexpensive and simple test. The California Division of Highways recognized the desirability of using the small Charpy specimen for routine estimation of toughness, and therefore undertook this research.

3. Fracture Control

Two basic approaches to fracture control are available. The first, based on fracture mechanics theory, attempts to prevent development of cracks of critical size by insuring a permissible combination of toughness, initial flaw size, and crack growth rate for a desired structure life and service environment. This approach depends largely on the ability of nondestructive inspection to detect all flaws larger than the specified allowable initial flaw size. The other method attempts to guarantee the occurrence of "yield failure" prior to brittle fracturing at a crack of any length, by requiring <u>tougher</u> steels. Although this approach minimizes the nondestructive inspection requirements, the higher toughness levels required may prove too costly for routine application.

In either of the above approaches to fracture control, fracture toughness (K_{Ic}) determination is a necessity.

4. Toughness Measurement Using the Compact Tension Test

The compact tension test measures a steel's "critical plane strain fracture toughness" (K_{Ic}) by subjecting a specimen containing a constrained precrack to a tensile load. The steel's K_{Ic} value is defined by a specified deviation from linearity in the plot of applied load versus notch opening. In order to provide the necessary degree of constraint, a specimen thickness requirement is imposed, namely;

$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma ys}\right)^2, \qquad \text{Eq. (12)}$$

where: B = minimum specimen thickness (in.)

K_{Ic} = measured critical plane strain fracture toughness (ksi $\sqrt{in}$)

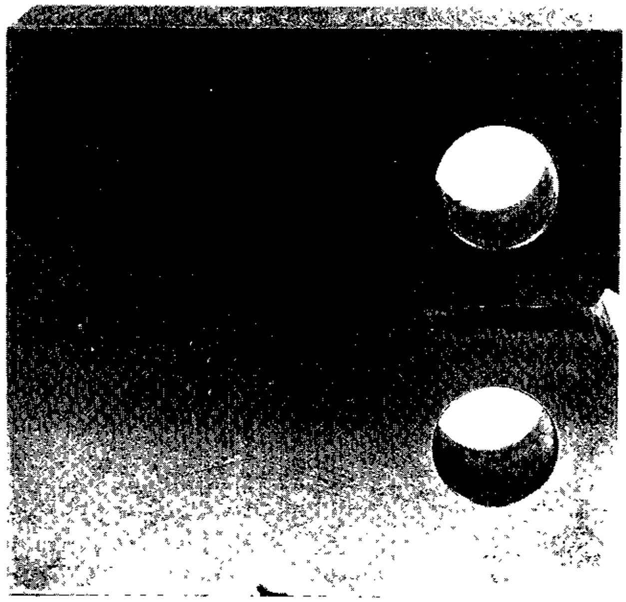
σys = tensile yield strength at same temperature and loading rate as K_{Ic} test (ksi).

When the above criteria is met, a "plane strain" condition should exist in the test specimen, thereby enabling the determination of critical plane strain fracture toughness (K_{IC}).

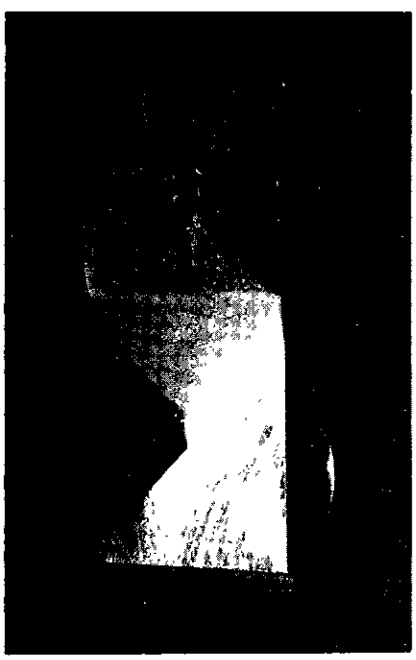
A plane strain condition is characterized by a high degree of constraint and an absence of thru-thickness deformation at the flaw. Failure resulting from a plane strain state of stress exhibits a flat, planar fracture surface, free from the large angular "shear lips" which usually accompany the more conventional yield-type failure (Figure 3). In fact, fracture face appearance is such a good indicator of the failure mode that certain toughness test results are often expressed in terms of it (e.g., "percent shear").

Because fracture toughness and yield strength vary with temperature, and because the minimum required specimen thickness is a function of fracture toughness and yield strength (Equation (12)), it was necessary to use different specimen thicknesses for the different test temperature ranges. This testing program utilized one-inch thick compact tension specimens for the lower testing temperatures and two-inch thick specimens for the higher test temperatures. But these efforts to meet the validity criteria from Equation (12) were not always successful, because validity cannot be checked until after each test has been completed. ASTM E399-72 specifies several other criteria for a valid test based on fatigue crack shape, fatigue load levels, and other testing variables. Although many of our test results failed to fulfill some or all of the above validity criteria, it is felt that these test results are still meaningful in light of the fact that validity criteria are usually considered somewhat conservative. The specimen size criteria (Equation (12)) is especially questionable, since it precludes the K_{IC} testing of lower strength steels whose rolled thicknesses are not great enough to provide specimens able to meet the criteria set forth in Equation (11). Some have asserted (9) that reduced thickness K_{IC} test specimens can yield values within $\pm 15\%$ of the "valid" K_{IC} measurement and that this degree of accuracy can prove useful for engineering approximations of K_{IC}.

If a group of K_{IC} tests are run over a range of test temperatures, a "lower shelf" value will be found to exist at the lower end of the test temperature range (see Figures 21 through 27 in the Appendix). Material toughness characteristics should always be such that this lower shelf occurs at some temperature below the lowest expected service temperature of the highway bridge. Because K_{IC} decreases with decreasing test temperature, it is important that the K_{IC} value for design use be measured at or below the lowest expected service temperature for that steel.



a. Compact Tension Specimen



b. Fracture Face
(Tough material)

c. Fracture Face
(Brittle material)

FIGURE 3. COMPACT TENSION SPECIMEN CHARACTERISTICS

Strain (loading) rate is also an important fracture toughness consideration. Yield strength generally increases as strain rate is increased. Hence "σ" in Equation (11) can be greater and the effective toughness of the material appears to decrease. In other words, a material appears less tough in a dynamic or impact test than in a static test. It is generally believed that the loading rate of the fracture toughness test should be selected in accordance with the actual strain rate imposed by highway bridge loads. However, two opposing theories exist regarding the applicable loading rate. The first holds that bridges are subjected to relatively slow loading rates except in such instances as an earthquake, the breaking of a heavy ruck's axle, etc.; and that designing against the rarity of such incidents is not economically feasible.

The second contends (1)(8) that, although the "causative" loading rate on the overall structure may be relatively slow (static), an active crack front is always subjected to a dynamic strain rate during increments of crack growth whether they be short increments associated with conventional fatigue crack growth, or longer crack advancements resulting from an active crack penetrating a localized zone of low toughness, or a void area.

This study deals entirely with the currently accepted method (ASTM E399) of static testing for K_{IC} and would therefore be in accordance with the slow loading rate theory presented above. This is not necessarily the most conservative nor realistic check test that could be employed (the slower loading rate test indicates greater material toughness than is indicated by the impact test), but it is the only fracture toughness measurement method per se, currently standardized through ASTM (E399). It is often argued that because brittle fractures have occurred under static rates of loading, a static K_{IC} laboratory test should be used to evaluate the steel. The undesirable aspect of the statically loaded test, however, is its failure to simulate an actual service cracking situation in the sense that no load is sustained to drive the crack. Rather, the test specimen load is partially relieved with each instance of crack extension, thereby allowing the crack to arrest due to loss of the driving load rather than to material toughness. The head speed of the testing machine is simply too slow to "catch up" with the rapid specimen relaxation resulting from crack extension. However, in those service situations where brittle fracture seemed to be the result of static loading, the structural dead load was always acting to advance the crack, and crack arrest due to loss of the crack-driving load was not a consideration. It is evident, then, that the ability of a static laboratory test to duplicate the service loading situation is limited.

Charpy V-notch impact requirements recently adopted by the American Association of State Highway and Transportation Officials (AASHTO) for bridge steels are based on the belief (18) that bridges experience crack trip strain rates somewhere intermediate between the static and the dynamic rates. Their Charpy V-notch energy requirements are therefore lessened to account for the fact that the test is run at the dynamic (impact) strain rate, which is a more severe condition than the material will ever see in service.

The relaxation of the Charpy testing requirements is accomplished by specifying an impact testing temperature above the service temperature by an amount consistent with Barsom's findings (4)(18) pertaining to loading rate effects on measured fracture toughness. This investigation, however, did not verify the existence of the linear upward shift in brittle-ductile transition temperature with increasing strain rate (4) which Barsom reported and which forms the basis for the new AASHTO Charpy requirements.

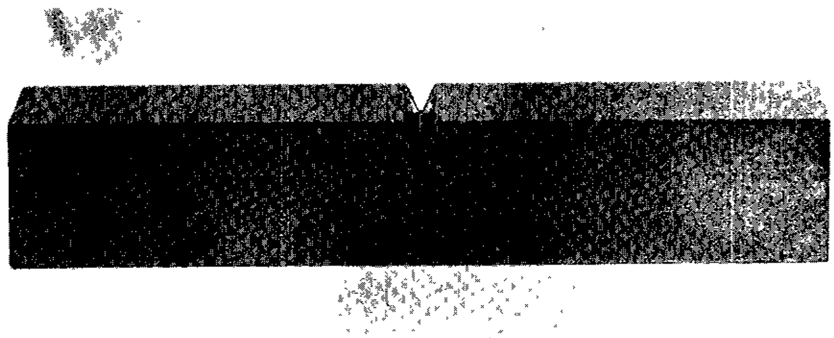
5. Toughness Estimation from the Charpy Impact Test

Both standard and precracked Charpy impact specimens were tested as part of this investigation. The standard (V-notch) test method has been used extensively as a toughness indicator since its inception during the World War II ship fracture crisis. The precracked Charpy test method, although the more desirable for its better simulation of a cracked service member, has not yet been standardized as an ASTM test method. Currently, ASTM Committee E-28 is working toward this end.

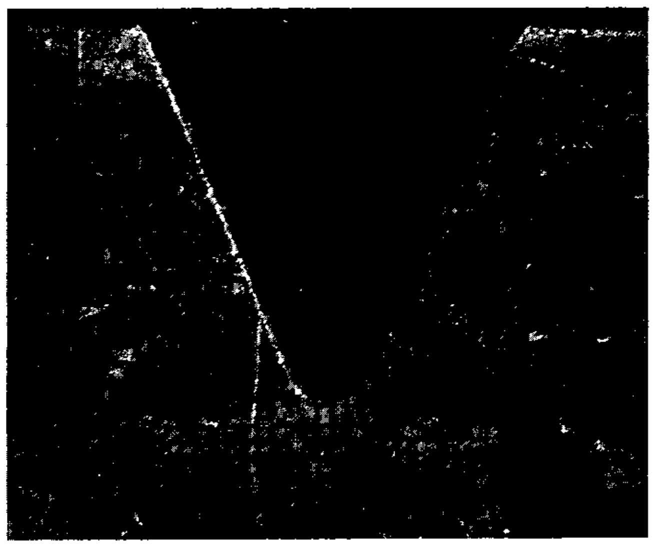
a. Charpy V-notch Impact Testing

Standard Charpy V-notch (Figure 4) impact energy values were previously compiled for some 100 heats of A517 steel sampled by the State of California. From these 100 heats, seven representing a broad toughness spectrum were selected for fracture toughness (K_{Ic}) testing in an effort to verify purported correlations between the two tests.

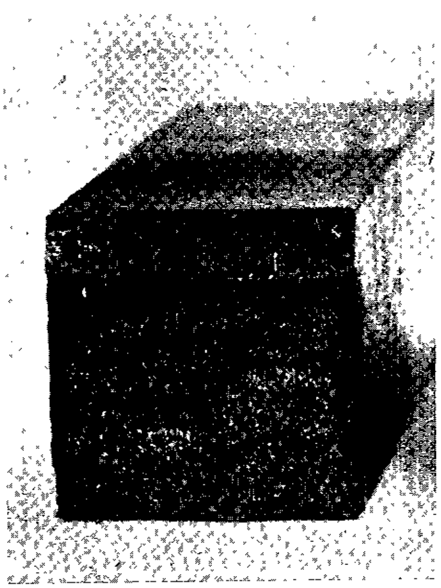
Various K_{Ic} - CVN correlations have been reported by other researchers. The most recent and probably the most prominent are those advanced by Barsom and Rolfe (4). These researchers developed two empirical correlations - one relating "upper shelf" CVN impact energies to "upper shelf" static K_{Ic} values, and another relating CVN values from the ductile-brittle "transition zone" of the CVN versus temperature curve, to K_{Ic} values at the same temperatures. Each of these correlations are discussed below.



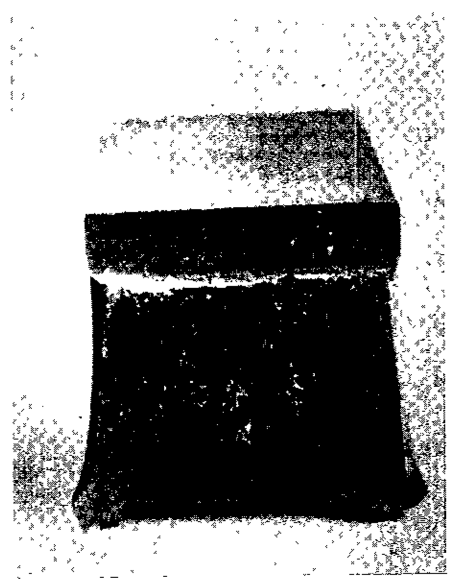
a. CVN Specimen



b. Machined V-notch root



c. Brittle Fracture Face



d. Tough Fracture Face

FIGURE 4 CVN SPECIMEN CHARACTERISTICS

The upper shelf correlation,

$$\left(\frac{K_{Ic}}{\sigma y}\right)^2 = \frac{5}{\sigma y}\left(CVN - \frac{\sigma y}{20}\right), \qquad \text{Eq. (13)}$$

where: K_{Ic} = ksi $\sqrt{in}$

σy = ksi

CVN = ft-lb,

was not able to be honestly evaluated by this research (Figure 5). None of the steel heats investigated exhibited low enough toughness (K_{Ic}) values in the upper shelf temperature range to provide valid K_{Ic} measurements according to the Equation (11) criteria. The original work by Barsom and Rolfe which lead to the upper shelf correlation in Equation (13) was based on "subthickness" K_{Ic} specimens (9) in evaluating the tougher steels. These specimens met the ASTM E399 dimensional requirements, except for the specimen thickness, which was necessarily limited to the thickness of the test material. Since the failure mode in the "upper shelf" temperature range is always "dimple rupture" (shear in the plane strain fracture mode), cleavage (brittle) fracture cannot be induced, no matter how thick the specimen is made, at temperatures in the upper shelf range. Based on this laboratory's testing experience, steels are not often tough enough to exhibit upper shelf behavior at critical service temperatures. Therefore, the usefulness of a K_{Ic}-CVN correlation for upper shelf conditions is limited.

Plate	K_{Ic} (ksi$\sqrt{in}$)	CVN (ft-lb)	σy (ksi)	$\frac{CVN}{\sigma y}$	$\left(\frac{K_{Ic}}{\sigma y}\right)^2$
A	120↑	50↑	112	.446	1.14
AL	120↑	40↑	100	.400	1.44
L	140↑	80	110	.725	1.61
M	120↑	67	125	.535	0.92
R	120↑	60	110	.545	1.19
Z	140↑	55	115	.477	1.49

Note: Barsom and Rolfe originally developed the upper shelf correlation for steels from 110-246 ksi yield strength.

Table I. Upper Shelf Correlation Data

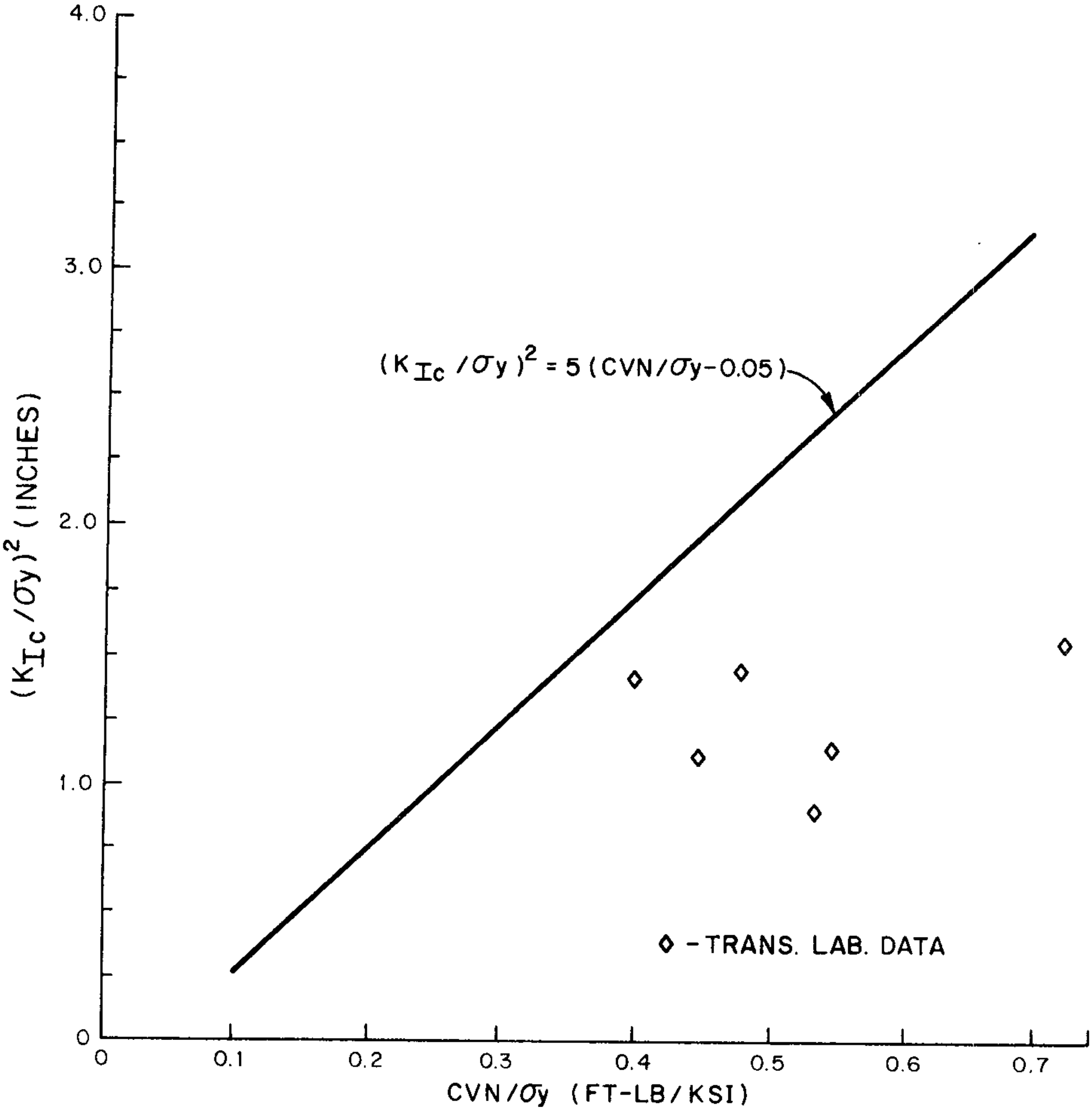


Fig. 5 AGREEMENT OF TRANSPORTATION LABORATORY DATA WITH REPORTED "UPPER SHELF" CORRELATION

The "transition zone" correlation,

$$\frac{K_{Ic}^{2}}{E} = 2\ (CVN)^{3/2}, \qquad \text{Eq. (14)}$$

where: K_{Ic} = psi $\sqrt{in}$

E = psi

CVN = ft-lbs,

on the other hand, provides a means of relating CVN values to K_{Ic} values in a temperature range more likely to include the critical service temperature as shown in Figure 6, Equation (14), and provides a rather conservative lower bound curve for the data obtained in this project. Also shown in Figure 6 is a transition zone correlation expression developed by Sailors and Corten (7),

$$K_{Ic} = 15.5\ \sqrt{CVN}, \qquad \text{where: } K_{Ic} = \text{ksi } \sqrt{in} \qquad \text{Eq. (15)}$$

CVN = ft-lb

This expression provides a better fit lower bound curve for the data obtained from this research. Lower bound curves should be used to define CVN-K_{Ic} relationships because errors in Charpy testing normally result in energy values on the high side.

It is often considered advantageous to measure specimen lateral expansion (LE) rather than pendulum energy loss because the later measurement is vulnerable to inaccuracies arising from testing machine malfunction and/or post fracture interference of the broken specimen halves with the out-swing of the pendulum. As noted earlier, an LE measurement of 15 mils was previously considered sufficient to guarantee nonbrittle behavior for all strengths of materials. This assertion has since been discredited (13), and many now accept that LE requirements, like impact energy requirements, should be "customized" for each thickness and material strength level. The findings of this study verified the lack of validity of the 15 mil theory, as two of the seven heats exhibited the 15 mil lateral expansion at temperatures below the NDTT. Obviously, in these cases the 15 mil criteria would have permitted a dangerous condition to exist.

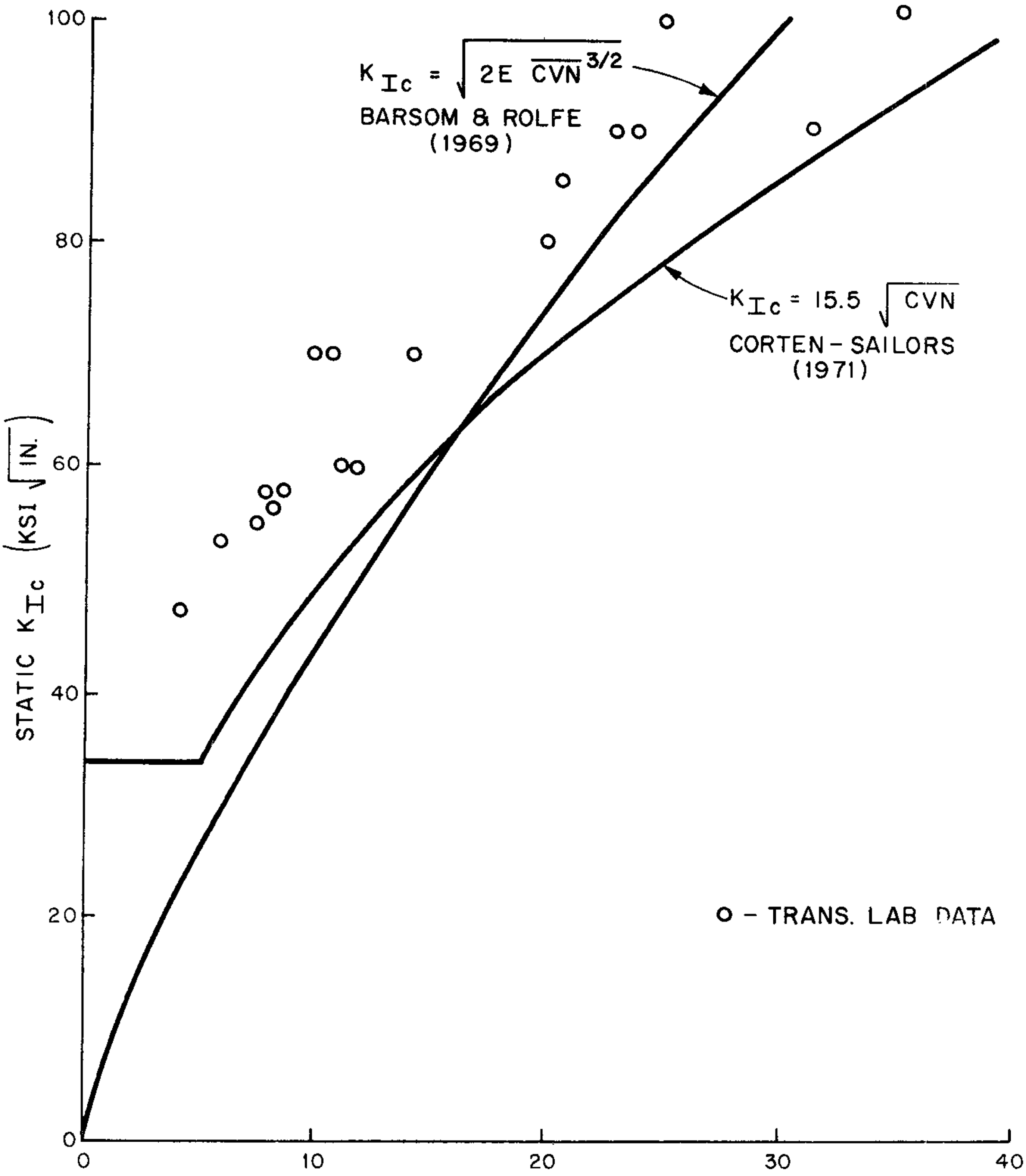


Fig.6 AGREEMENT OF TRANSPORTATION LABORATORY DATA WITH REPORTED CVN-K_{Ic} TRANSITION ZONE CORRELATIONS

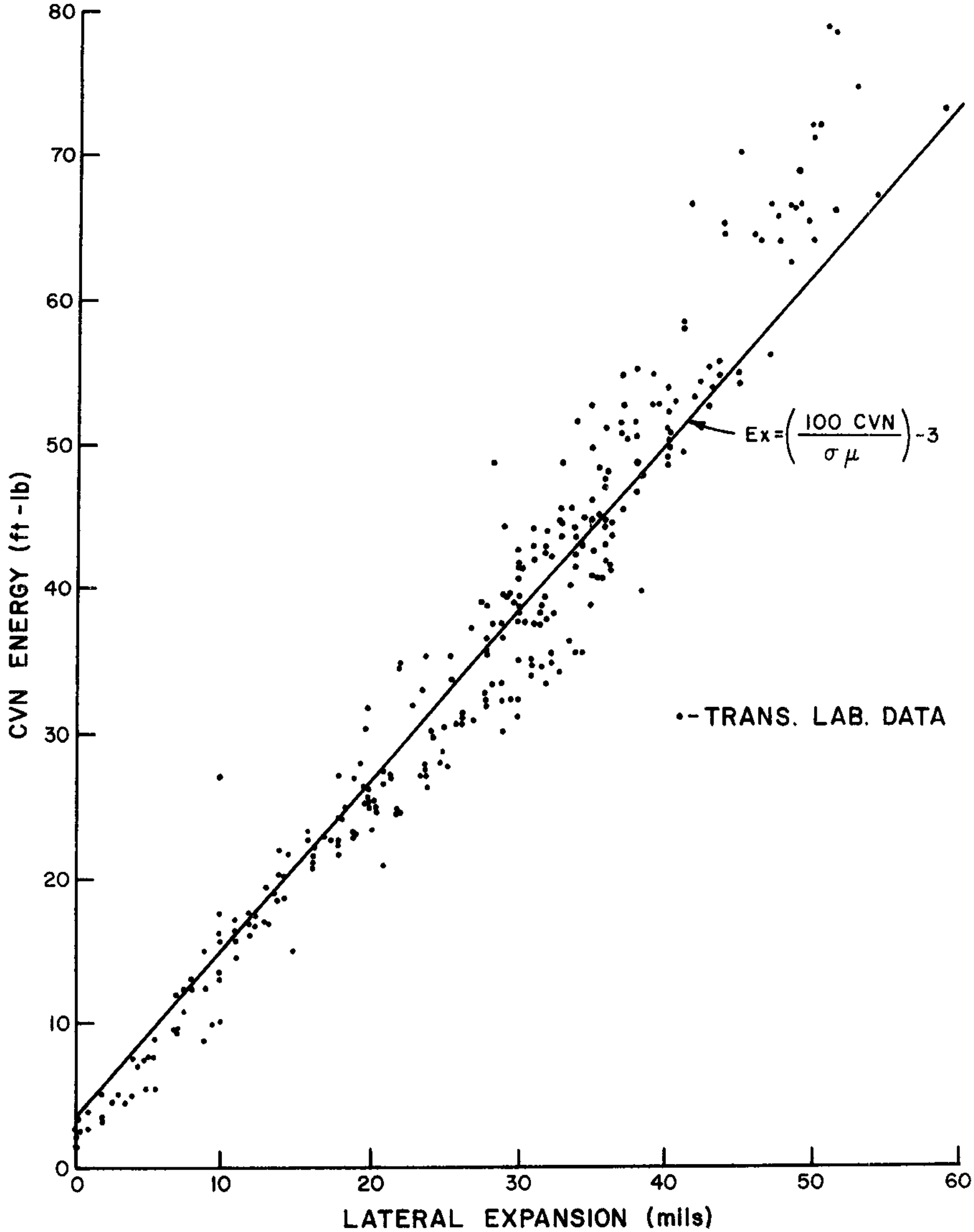
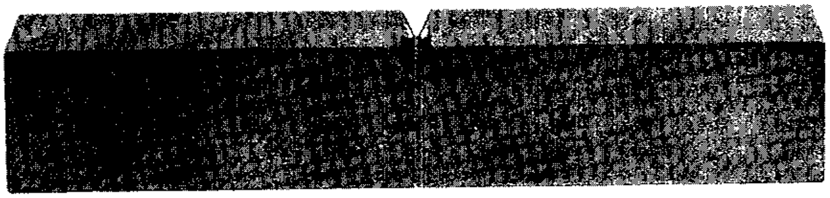
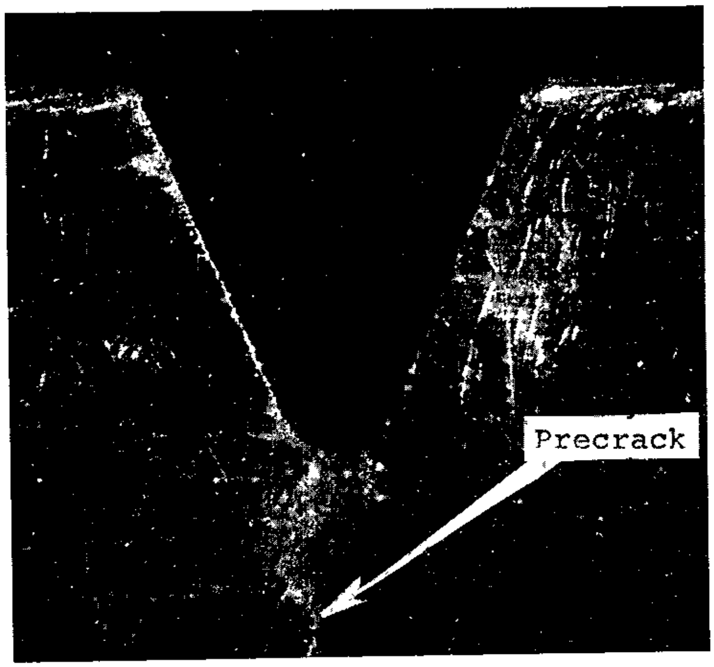


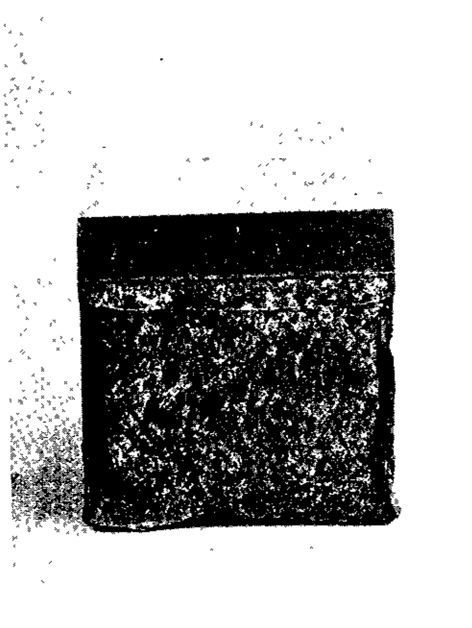
Fig. 7 LATERAL EXPANSION VS STANDARD CHARPY V-NOTCH (CVN) ENERGY



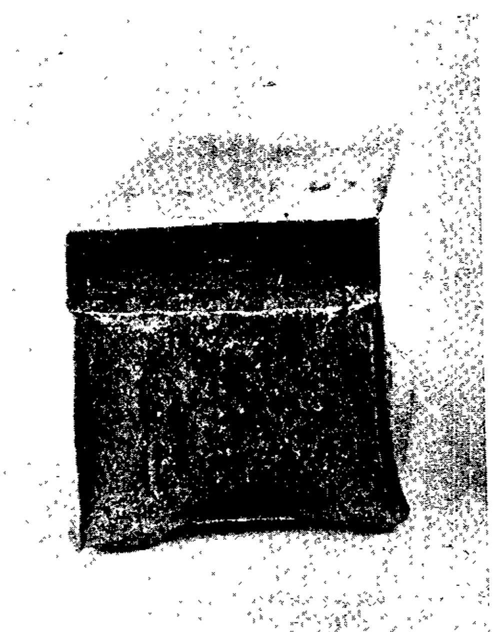
a. PCI Specimen



b. Notch With Precrack



c. Brittle Fracture Face



d. Tough Fracture Face

FIGURE 8. PCI SPECIMEN CHARACTERISTICS

An expression relating lateral expansion to energy absorption in Charpy V-notch specimens from the seven steel heats studied herein is presented below and in Figure 7:

$$LE = \left(\frac{100\ CVN}{\sigma u}\right) - 3,$$

where: LE = mils
CVN = ft-lbs
σu = ksi.

b. Precracked Charpy Impact Testing

The PCI specimen is simply the standard Charpy specimen which has been fatigue loaded to initiate a crack from the bottom of the machined V-notch (Figure 8). This test understandably, better simulates the critical service condition (i.e., a cracked plate). However, in the past the inability to control the depth of the specimen precrack has been cited as a major drawback to this test. Several precracking machines are now on the market which are able to automatically effect fatigue precracks to prescribed depths in the Charpy specimen. It has been shown (14) that the brittle-ductile transition temperature from the PCI versus temperature curve corresponds to the nil ductility transition temperature (NDTT) defined by the "drop weight-NDT" test. Since a basic fracture toughness requirement is that the NDTT of a material be below its lowest expected service temperature, this quick, simple, and inexpensive method of NDTT determination is of great value. Use of the precracked Charpy specimen also minimizes the possibility that highly "notch-sensitive" steels will find their way into service. Notch sensitivity is simply the degree to which impact energy or toughness decreases with decreasing notch root radius. The precracked Charpy specimen offers the minimum notch root radius (i.e., sharpest possible notch) and therefore imposes the most severe and realistic test on the material. Our testing of A514/A517 steels has disclosed materials which exhibit "acceptable" (nonbrittle) standard Charpy V-notch test behavior that corresponds to "lower shelf" (brittle) behavior in the PCI specimen at the same temperature (Figure 9). In these cases, notch sensitivity is great and the standard Charpy V-notch specimen would not expose the dangerous condition that exists when a crack is present in a structural member.

Because the PCI test provides a more realistic indication of material toughness, it was considered desirable to establish a correlation between K_{IC} and PCI measurements.

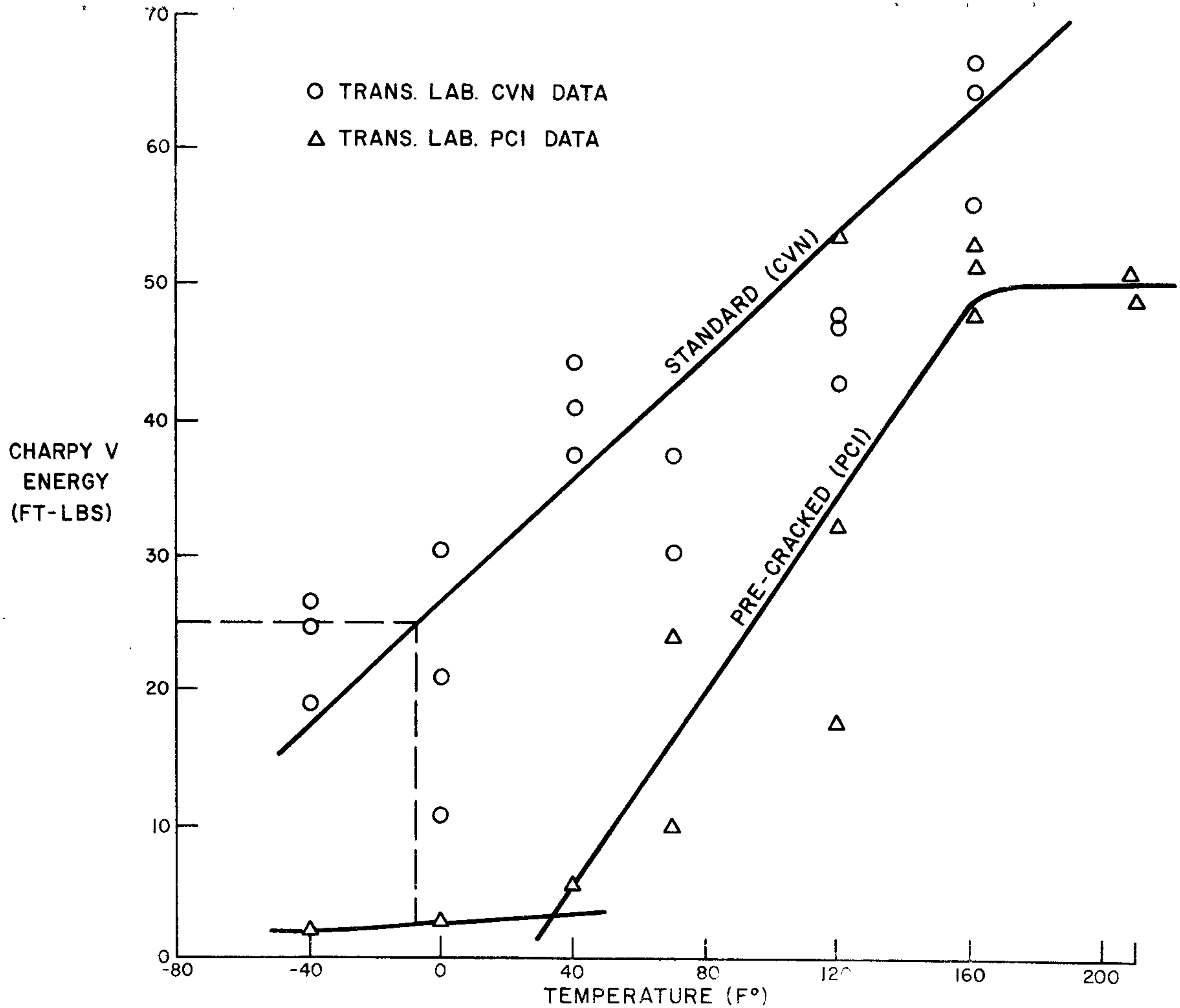


Fig. 9 EXAMPLE OF MISLEADING CVN TEST RESULTS

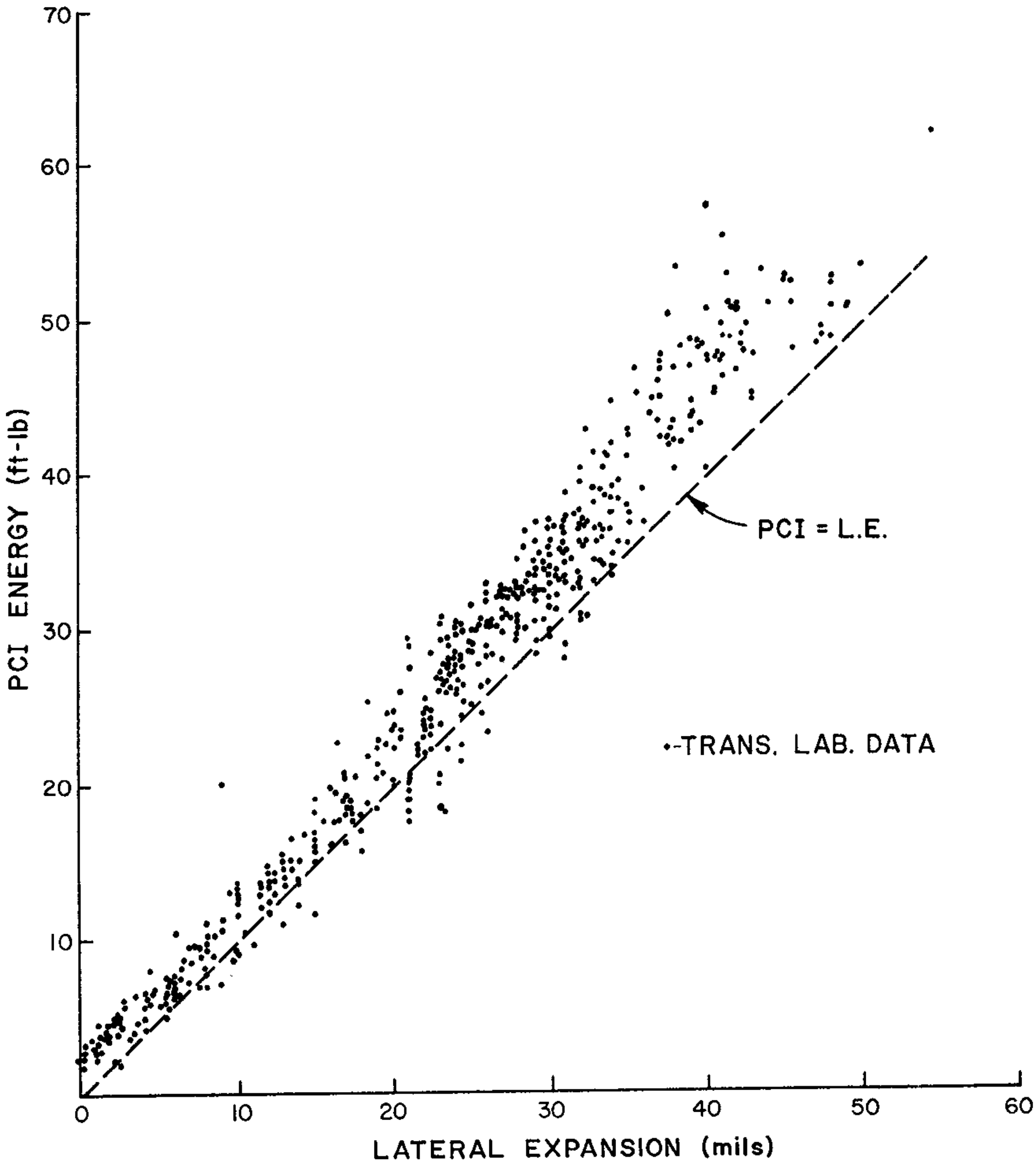


Fig.10 LATERAL EXPANSION VS PRECRACKED CHARPY IMPACT (PCI) ENERGY

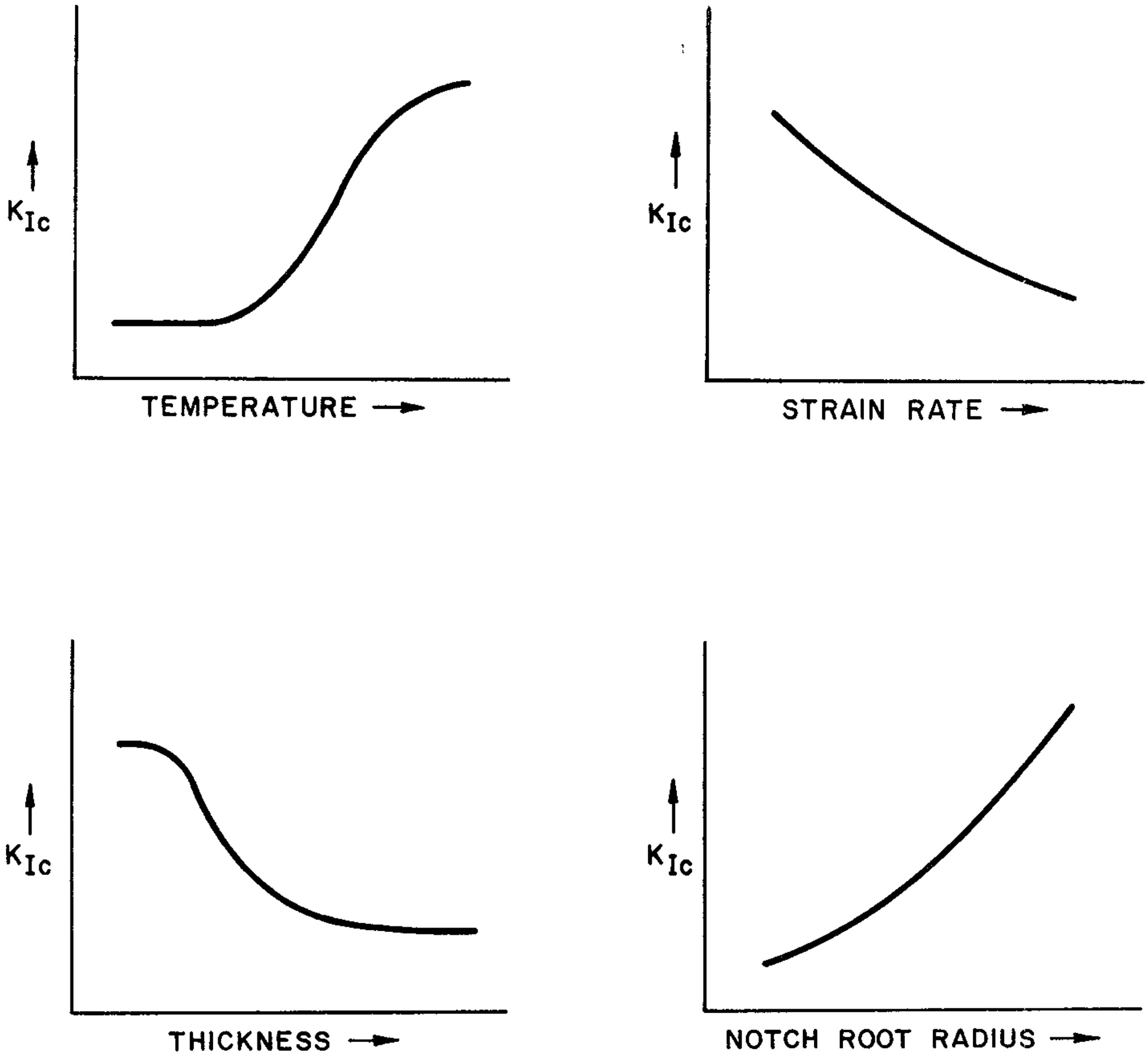


Fig. 11 EFFECTS OF TEST VARIABLES ON K_{Ic} MEASUREMENT

the flaw-detection capability of an inspection program is limited by both the capabilities of the particular inspection equipment and technique used, and the less than 100% inspection coverage usually realized.

b. Welding

Although welding is the most desirable steel joining method in many aspects, it is the most dangerous method in terms of the probability of undetected flaws existing in the completed joint.

Until welding procedures are perfected to the point where the probability of weld-induced flaws is minimized, comprehensive inspection programs and adequate toughness controls should be maintained.

Welding methods and procedures that result in low toughness levels should not be used. In an effort to learn more about the effects of welding on the toughness of steel, this Laboratory has included in its current research program an investigation of welding of high yield grade ($90 \text{ ksi} \leq \sigma_{ys} \leq 120 \text{ ksi}$) bridge steels.

c. Service Environment

Two important environmental factors that should be considered when establishing toughness levels for steels are (1) the lowest anticipated service temperature for the steel and (2) the nature of the service environment.

It is imperative that toughness evaluation testing be done at or below the lowest anticipated service temperature for the intended structure, as toughness is a temperature-dependent property.

The corrosiveness of the service environment may also influence toughness requirements by increasing the crack growth rate, thereby necessitating higher toughness levels if the usual service life is desired.

Hydrogen-rich environments can also tend to embrittle some steels, thereby increasing the crack growth rate and, again, necessitating higher toughness levels if the usual structure life is desired.

d. Design Features

Frequently, undesirable design features, considered unavoidable by the designer, create situations where higher toughness requirements are necessary. These situations include the use of (1) thick flange sections, (2) welding details that are likely strength, steels. Therefore, most of these structures are possibly too young to enable fair assessment of the effects of any toughness deficiencies that might exist.

It is seen, then, that in-service structures may be grouped into two major categories;

(1) "Old Structures" (i.e. primarily non-welded, structures of lower strength steels such as A7 and A36)

These structures have been afforded a long life by being subjected to stress levels and stress fluctuation ranges that have not been capable of growing a flaw to a critical size thus far in the service life.

(2) "New Structures" (i.e., of welded and/or high strength steel construction)

These structures may still be too young to manifest toughness inadequacies.

Associated with any fracture control program is a degree of risk. It is difficult to determine absolute degrees of risk, but relative degrees of risk are definable. A structure subject to steel toughness controls and extensive nondestructive inspection requirements will surely pose a lesser degree of risk than a structure built under no such controls. Just what level of toughness control and inspection is justified is an area of controversy. At one extreme, where sufficient toughness is required to guarantee "thru-thickness yielding" at any crack tip, the risk of brittle fracturing is minimized. At the other extreme, where no precautions are taken to deter brittle fracturing, there exists the high risk level associated with the use of low-toughness steel and a limited inspection program. Although the thru-thickness yielding toughness criteria is felt to be too demanding by some steel producers, it has been met by certain steel heats in past testing. If the "thru-thickness yielding" criteria is considered too demanding, as reflected by steel cost, a statistically attractive fracture mechanics approach, which considers critical crack sizes, crack growth rates, and desired structure life, must be employed. The fracture mechanics approach, however, should be avoided if possible, because of the uncertainties associated with stress estimations, initial crack size determinations, and crack growth progress measurements. Some of the factors that contribute to this uncertainty are:

(1) the fact that on larger structures inspection other than visual is often limited to less than 100% of each primary weld

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(2) the use of design details and fabrication and erection practices which either encourage resultant cracking or make inspection difficult

(3) the limited number of competent inspection personnel available.

As each of these areas of uncertainty is eliminated or minimized, the practicality and reliability of a fracture mechanics approach to the problem is increased.

Ultimately, the determination of the degree of risk associated with any structure must take into consideration <u>all</u> of the factors discussed herein.

to result in cracking and high residual stresses in primary tension members, and (3) conditions where transverse plate properties are taxed, i.e., box girder bottom flanges. (With respect to items (1) and (2), it is generally agreed that the required toughness level is a function of the applied stress and the thickness of the member.)

e. Redundancy of Structural Members

In situations such as multiple, parallel girders with cross framing, where sufficient structural redundancy exists to discourage catastrophic failure, material toughness and inspection requirements could possibly be relaxed. Where redundancy is lacking, such as in the case of the steel box girder with full width stiffened bottom flange plate, material toughness requirements should necessarily be more stringent and/or a more extensive inspection and higher toughness would become a major consideration in the overall bridge cost.

The degree of redundancy (in terms of number of parallel girders and effectiveness of the cross framing in transferring load) required to prevent catastrophic failure is a question that should only be answered by the designer.

f. Degree of Risk

Just what level of risk should be tolerated in a finished structure is surely a subject of controversy. Many will argue that steel toughness requirements are not necessary at all, based on the fact that history has produced so few bridge failures attributable to lack of toughness. This argument may be refuted on the following grounds. Field field measurements have (21)(22) shown live load stress fluctuation in highway bridges to seldom exceed 8 ksi. The slow crack growth rates commensurate with these low stress ranges have possibly afforded most of the older structures a long (but not infinite) life. Newer structures, quite possibly, are only subject to the same low stress fluctuation range, but are subject to the effects of relatively new and different aspects of bridge construction, such as (1) residual stresses from welding, (2) conditions of high constraint resulting from the use of thicker sections and higher strength steels, and (3) complicated stress situations arising from complex design details.

Although toughness is necessary in virtually all steels, it is of greater concern in the higher yield strength grades and thicker plate sections, where, heretofore, the inherent toughness of as-produced steels has occasionally proven inadequate. Only in recent years, when bridge design has been more highly influenced by aesthetics, materials economy, and greater concern for public safety, have designers been routinely using higher

8. Additional Information

Uncertainty in fracture control programs for structural steel arises primarily from difficulty in relating laboratory test results to in-service performance. The basic justification for using small laboratory test specimens to indicate the performance of large bridge girders is the argument that maximum constraint is present in the laboratory specimen so that in the actual bridge girder the degree of constraint (fracture susceptibility) can be no greater. With constraint the same in each case, the all-important toughness-temperature relationship becomes definable.

But in addition to the effects of temperature, thickness, loading rate, and notch root radius all discussed above, other factors influencing susceptibility to brittle fracture are worthy of discussion.

a. Flaws

Flaws are inherent in fabricated steel structures. Unavoidable, undetected flaws can be expected in parent metal and in welds. Toughness is nothing more than a material's ability to withstand the propagation of these flaws. The concern for flaws is greater in higher strength steels and, accordingly, greater reliance is placed on improved toughness for protection in these steels.

From its initial size, a flaw can grow to critical proportions through such mechanisms as fatigue or stress corrosion. A material's toughness must be great enough to enable it to tolerate any flaw growth that will occur during the design life of the structure.

Steel inspection programs must be established which will guarantee (within certain statistical limits) that no flaws larger than a given size will remain in the inspected areas after inspection. This would allow designers to assume a maximum flaw size and employ fracture mechanics design theory (Equation (11)), if desired.

The Transportation Laboratory's current research program will include a project devoted specifically to the statistical determination of probable minimum detectable flaw sizes for each of the nondestructive testing methods used by this Laboratory.

It is the current practice of this Laboratory to rely primarily on radiographic and ultrasonic inspection of joints in primary load-carrying members. Supplemental inspection using dye penetrant and magnetic particle methods is also available. It must be realized, however, that in the case of large structures the cost of this inspection can sometimes limit its application to only ten percent of each primary weld in the structure. Thus

It is clearly seen (Figure 11) that four primary test conditions affect fracture toughness measurements; 1) notch root radius, 2) thickness, 3) strain rate, and 4) temperature. No absolute values are cited for thickness and strain rate conditions because further research is needed in these areas.

7. Thru-Thickness Yielding Criteria

The level of toughness necessary in a material to enable it to perform as intended is subject to controversy. One criteria, mentioned earlier, attempts to insure plane stress conditions or, in other words, thru-thickness yielding of the member. This theory is based on work by Hahn and Rosenfield (6), who observed that a significant increase in the rate at which thru-the-thickness deformation occurs in a plate is realized when

$$K_{Ic} = \sigma y \sqrt{t}, \qquad \text{where: } K_{Ic} = \text{ksi}\sqrt{\text{in}} \qquad \text{Eq. (17)}$$

$$\sigma y = \text{ksi}$$

$$t = \text{inches}.$$

The level of toughness defined by Equation (17) should, therefore, insure the conventional yielding type of failure and minimize the probability of sub-yield stress fracturing at service temperatures equaling or exceeding the temperature of the K_{Ic} determination. This K_{Ic} value represents the highest value for which a plane strain failure mode governs, and, presumably, was assumed to equal the K_{Ic} "upper shelf" toughness value when used by the Rolfe, Gensamer and Barsom (19) as the basis for CVN upper shelf values.

They also applied the thru-thickness yielding criteria to their empirical relationship (Equation (14)) between K_{Ic} and CVN values from the "transition" temperature regions of the CVN and K_{Ic} versus temperature curves.

Thus, two criteria for toughness adequacy were proposed in terms of Charpy V-notch impact energy absorption. The validity and practicality of each of these criteria are further discussed in the Appendix. If the K_{Ic} values calculated from Equation (8) (using temperature dependent values of σy) are plotted on the K_{Ic} versus temperature grid, they fall near or above the projected upper shelf for the K_{Ic} (measured) values. This suggests that the thru-thickness yielding criteria, if met, should insure upper shelf (very ductile) behavior.

The following expression was found to relate transition zone PCI energies to transition zone K_{Ic} values for the seven heats of A514/A517 steel investigated herein;

$$\frac{{K_{Ic}}^2}{E} = 18 \text{ PCI}, \qquad \text{Eq. (16)}$$

where: K_{Ic} = psi $\sqrt{in}$

E = psi

PCI = ft-lb.

The graphical presentation of this expression as it fits the test data is shown in Figure 31 of the Appendix.

The ability of PCI values to correlate to K_{Ic} measurements comes as no surprise because both tests utilize a precracked test specimen.

As in the case of the V-notch specimen, a favorable alternative to the expression of PCI test results in terms of energy absorption (foot-pounds), is the measurement of the lateral expansion (LE) evident in the broken Charpy specimen halves. This measurement is especially useful in the case of the PCI test, where a 1:1 relationship has been found to exist between PCI energy absorption and lateral expansion (Figure 10) for the A517 steel studied herein.

6. Toughness Testing Summary

The ideal toughness test would include the following features:

a. a specimen of small size and simple geometry for economy in machining

b. a notch effect in the form of a precrack

c. adequate thickness to provide a state of stress similar to that encountered in that particular service situation

d. a crack tip strain rate equal to that produced by service loads

e. a testing temperature equal to or below the lowest expected service temperature.

VII. APPENDIX

"Fracture Toughness of High Strength Steels

for

Bridge Construction"

by

C. E. Hartbower

and

W. G. Reuter

31 January 1973

ADVANCED TECHNOLOGY
AEROJET SOLID PROPULSION COMPANY
SACRAMENTO, CALIFORNIA 95813

FRACTURE TOUGHNESS OF HIGH-STRENGTH STEELS FOR BRIDGE CONSTRUCTION

by

C. E. Hartbower

and

W. G. Reuter

In cooperation with State of California, Business and Transportation Agency, Department of Public Works, Division of Highways

PREFACE

ASTM Specification A517, as revised in 1970, has a requirement for Charpy V-notch impact testing. The criterion for compliance is 15 mils of lateral expansion at the temperature specified on the order but no higher than plus 32°F. ASTM Specification A514, revised in 1970, which provides quenched-and-tempered steel plate for bridges (and other applications) has no toughness requirement.

The 15-mils lateral-expansion requirement is based on research, first at Lehigh University, and more recently at the U.S. Steel Applied Research Laboratory. For one-inch-thick A514/517 plate at 100 ksi yield strength, 15 mils approximately corresponds to the Charpy V-notch impact energy for through-thickness yielding. However, for A514/517 plate of thickness greater than 1 inch, this criterion has no more significance than an arbitrary Charpy V-notch specification of 22 ft-lb.

State of California bridge designers are seeking a more conservative toughness requirement that will give a degree of quality assurance that the specifications presently do not provide. The study described in this report was focused on the findings and recommendations of U.S. Steel researches that went beyond the arbitrary 15-mil lateral-expansion criterion; the U.S. Steel researches proposed criteria based on the joint consideration of yield strength and plate thickness. The objective of the studies was to establish a toughness criterion which would minimize the possibility of brittle fracture in critical structural members by utilizing the fracture-mechanics concept of through-thickness yielding.

FRACTURE TOUGHNESS OF HIGH-STRENGTH STEELS FOR BRIDGE CONSTRUCTION

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FRACTURE TOUGHNESS OF HIGH STRENGTH STEELS USED IN BRIDGE CONSTRUCTION

SUMMARY OF FINDINGS

Purpose and scope of the study. The objective of this program was to (1) investigate the possibility of a 1:1 correlation between the transition temperatures as indicated by precrack-Charpy and compact-tension tests of ASTM A514/517 steel, (2) verify an empirical relationship between Charpy impact test results and plane-strain fracture toughness (K_{Ic}) as reported by the U.S. Steel Applied Research Laboratory, and (3) evaluate the concept of through-the-thickness yielding as an accept-reject criterion for steel procurement.

Of seven steels investigated, two were ASTM A514-F, one was A517-F, two were A514-H and two were A517-H, with four of the steels from Lukens and three from U.S. Steel. Except for one 2-in.-thick A514-H plate, all were 2-1/4-in. thick. The steels were tested using ASTM E399 compact-tension specimens and procedure, and using standard Charpy (10-mil radius) V-notch impact and fatigue-precracked Charpy impact test specimens. Each specimen type was to be tested over a sufficient range to encompass the ductile-to-brittle transition-temperature range.

Correlation of precrack Charpy impact and static compact-tension transition temperatures. The displacement between precrack Charpy impact transition curves and compact-tension K_{Ic} transition behavior varied markedly from heat to heat in the seven steels investigated in this study. One steel, a heat of A517-F (Lukens Plate A), indicated a displacement of 240°F, and another steel, a heat of A514-F (U.S. Steel Plate M), indicated a displacement of 160°F. The other four steels (including heats of A514-F, A514-H and A517-H) had transition-temperature displacements of 50 to 80°F. One heat of A517-H (Lukens Plate Q) was anomalous in its behavior in that it showed no transition in either compact-tension tests run between 0 and plus 200°F or in Charpy tests between 0 and plus 360°F.

The marked displacement between precrack Charpy impact transition curves and K_{Ic} transition behavior of the steels of this investigation could not have been anticipated from the U.S. Steel researches. Although Shoemaker and Rolfe clearly showed a marked rate-of-loading effect in three of the steels they investigated (A36, ABS-C and A302B), the effect was not great in the one heat of A517-F steel investigated (see Table 1). As a result of extreme strain-rate sensitivity of some heats of A517/514 steel, one cannot predict the temperature at which the static compact-tension K_{Ic} transition will occur based on Charpy impact tests alone.

Empirical upper-shelf CVN-K_{Ic} correlation. U.S. Steel researches which evolved an empirical correlation between standard Charpy V-notch impact energy values and static plane-strain K_{Ic} values involved a single heat of A517-F steel (heat 73A377). The K_{Ic} testing was done with bend specimens. Some of the specimens upon which the correlation was based were valid K_{Ic} tests according to ASTM E399 criteria; however, the particular U.S. Steel heat of A517-F used in their researches was far too tough to permit valid K_{Ic} measurements in the thickness of the available plate. Nevertheless, the U.S. Steel A517-F data complied with the empirical relationship

$$(K_{Ic}/FTY)^2 = 5\ (CVN-FTY/20)/FTY$$

When Charpy V-notch (CVN) shelf-energy values as determined in this investigation of seven 2-1/2-in. thick plates were used to calculate K_{Ic}, the values were significantly higher than those measured at the highest temperatures tested in compact tension. This was not unexpected because at the highest temperatures investigated in compact tension testing, the fracture toughness was generally too high to permit valid K_{Ic} measurements in 2-1/4-in.-thick plate. Moreover, with one exception, the A514/517 heats investigated were strain-rate sensitive and, therefore, the Charpy V-notch impact shelves occurred at relatively high temperature. At such temperatures, it was not possible to obtain valid K_{Ic} data in 2-1/4-in.-thick plate.

In two heats of A514-F steel (U.S. Steel plates L and M) where the CVN upper shelf occurred below 75°F, it was possible to compare the calculated and measured K_{Ic} values at a common temperature, viz., plus 75°F. The comparison is shown in the following tabulation:

Plate No.	Yield Strength (ksi)	CVN Impact Temp. (°F)	CVN Impact Energy (ft-lb)	Calc. K_{Ic} (ksi-in.$^{\frac{1}{2}}$)	Measured 2-in. Compact Tension Temp. (°F)	Measured 2-in. Compact Tension $2.5(KQ/FTY)^2$ (in.)	Measured 2-in. Compact Tension KQ (ksi-in.$^{\frac{1}{2}}$)
M(ZU)	118	+75	67	190	+75	2.86	125.2
L(ZV)	109	+75	78	200	+75	3.27	125.7

From the above, it will be seen that at plus 75°F the toughness was too great for a valid K_{Ic} measurement in the 2-1/4-in. thick plate and, therefore, the measured values were low as compared with the calculated values based on the upper-shelf correlation.

Application of the upper-shelf CVN-K_{Ic} correlation was restricted by <u>strain-rate sensitivity</u>. As a result of strain-rate displacement, the temperature corresponding to the CVN upper-shelf was well above the static compact-tension K_{Ic} transition temperature. In practice, if an estimate of K_{Ic} is desired as a particular service temperature and the CVN upper-shelf occurs at a higher temperature, the K_{Ic} estimate based on the CVN-K_{Ic} upper-shelf correlation may be meaningless in terms of the actual K_{Ic} at the lowest anticipated service temperature. For example, if the transition in K_{Ic} behavior from low-toughness cleavage to high-toughness dimpled rupture were to start at or above the lowest anticipated service temperature and the CVN impact upper-shelf were to occur at a higher temperature, the estimated K_{Ic} value based on the CVN upper-shelf would be unrealistically high in terms of the K_{Ic} value at the service temperature. If, on the other hand, the K_{Ic} temperature transition occurred well below the specified service temperature, or if the CVN upper shelf occurred at or below the specified service temperature, then the estimated K_{Ic} value based on the CVN-K_{Ic} upper-shelf correlation would be useful. Thus, proper use of the upper-shelf correlation requires that Charpy data be taken at the lowest anticipated service temperature and one other higher temperature; if the measured CVN impact value at the lower temperature is not an upper-shelf value, the upper-shelf correlation should not be used.

<u>Transition-temperature-range correlation</u>. The U.S. Steel researches indicated an empirical relation between CVN and K_{Ic} in the low and transition-temperature range. This relation

$$K_{Ic}^{\ 2} = 2(CVN)^{3/2}$$

was based on data from five structural steels having room-temperature yield strengths ranging from 39 to 246 ksi. The steels included one heat of A517-F and two low-strength highly strain-rate-sensitive structural steels (ABS-C and A302-B). Scatter in the U.S. Steel correlation results were attributed to loading-rate effects. When valid K_{Ic} data from the seven A514/617 steels of this investigation were compared with the U.S. Steel findings, the usefulness of the U.S. Steel K_{Ic}-CVN transition-temperature-range correlation was verified. Precrack Charpy impact (PCI) data also were examined to eliminate the notch-acuity difference between the compact-tension and the Charpy testing. The following expression represented the lower bound of the scatter in the K_{Ic}-PCI plot:

$$KQ^2/E = 18 \cdot (PCI)$$

Through-thickness yielding criterion. U.S. Steel investigators have proposed a through-thickness-yielding criterion for acceptable toughness based on linear-elastic fracture mechanics concepts, utilizing the findings of a study by Hahn and Rosenfield for the Ship Structure Committee. Hahn and Rosenfield found that surface-displacement measurements indicated an increase in the rate at which through-thickness yielding accumulates relative to in-plane deformation when

$$(K/FTY)^2/B > 1$$

Hahn and Rosenfield concluded that this increase in rate may serve to identify a practical upper bound to the plane-strain regime. The U.S. Steel investigators used the above expression for through-thickness yielding and combined this expression with the upper-shelf correlation equation to give

$$CVN = FTY(B + 0.25)/5$$

The through-thickness-yielding criterion as proposed by the U.S. Steel investigators is applicable for steels developing full shelf energy in the Charpy test at or below the lowest anticipated service temperature. Five of the seven steels investigated did not develop upper shelf energy until the test temperature was above plus 200°F and, therefore, the question of whether they met the proposed criterion is academic from the standpoint of bridge construction. Two of the seven A514/517 steels developed shelf energies in the range of normal bridge service; these were both U.S. Steel A514F plate and met the through-thickness-yielding criterion based on the Charpy V-notch impact shelf energy.

As an alternative to the CVN upper-shelf correlation, the transition-temperature-range correlation was considered as a basis for establishing a through-thickness-yielding criterion. When Hahn and Rosenfield's expression was combined with the U.S. Steel transition-temperature correlation, the following relationship was obtained as a basis for a through-thickness-yielding criterion:

$$FTY^2 = 2(CVN)^{3/2} E/B$$

Both of the heats used in the U.S. Steel researches met this criterion. However, in this study, only two of seven steels investigated, viz., U.S. Steel A514-F plates L and M, met this criterion for through-thickness yielding. As a further check on the usefulness of this criterion, Charpy data from nine 1-1/2-in. plates of U.S. Steel A517-F were evaluated as to their compliance with the criterion; eight of the nine heats were indicated to have sufficient toughness for through-thickness yielding.

The use of Charpy V-notch (10-mil radius) specimens for purposes of estimating K_{Ic} values is unconservative in the case of the occasional heat of steel which is markedly affected by notch acuity. To assure a conservative criterion, Hahn and Rosenfield's expression was combined with a lower-bound PCI-K_{Ic} relationship to give the following through-thickness-yielding criterion in terms of precrack Charpy impact energy:

$$PCI = B \cdot FTY^2/18E$$

For a plate thickness of 2-1/4 in. this expression indicated the following minimum precrack Charpy energy levels for through-thickness yielding:

Thickness (in.)	Yield Strength (ksi)	Through-Thickness Yield Minimum PCI Energy (ft-lb)
2-1/4	100	43
	110	51
	120	60

Only U.S. Steel A514-F plate M came close to meeting this criterion for 2-1/4-in. thick plate; plate L was particularly sensitive to notch acuity and, consequently, failed to meet this criterion even for 1-in.-thickness. The A517-F heat used in the U.S. Steel research tested with precrack Charpy impact did not meet the requirement for 2-in.-thick plate. When precrack Charpy impact data from nine 1-1/2-in.-thick plates of U.S. Steel A517-F were evaluated as to their compliance with the criterion, eight were indicated to have sufficient toughness for through-thickness yielding.

When the plane-stress plastic-zone-size expression was used as a basis for establishing through-thickness yielding, the following criterion evolved:

$$W/A = FTY^2 \cdot 2\pi B/E$$

where W/A is the precrack Charpy impact test result in units of in-lb/in.^{2}. This expression, for all practical purposes, indicated the same precrack Charpy impact values for through-thickness yielding as the relationship based on the work of Hahn and Rosenfield.

Conclusions. The seven ASTM A514/517 steels investigated showed marked heat-to-heat variations in fracture behavior and, with one exception, markedly poorer fracture behavior than the two heats of ASTM A517-F used in the U.S. Steel researches. Heat-to-heat variations in the extent of strain-rate embrittlement precluded a 1:1 correlation between precrack Charpy impact and static compact-tension transition behavior. The empirical K_{Ic}-CVN relationship reported by U.S. Steel based on upper-shelf Charpy energy values could not be used in five of the seven steels tested because the Charpy upper shelf occurred well above bridge-service temperatures. The through-thickness-yielding criterion proposed by U.S. Steel investigators utilizes the upper-shelf correlation; therefore, this criterion is only applicable for steels developing full shelf energy in the Charpy test at or below the lowest anticipated service temperature. The through-thickness-yielding concept was evaluated using K_{Ic}-CV N transition-temperature correlations; useful criteria were established based on both the standard Charpy V-notch and the precrack Charpy impact tests.

INTRODUCTION

Purpose of the Study

The objective of this program was to (1) investigate the possibility of a 1:1 correlation between the transition temperatures as indicated by precrack-Charpy and compact-tension tests of bridge steels, (2) verify an empirical relationship between Charpy impact test results and plane-strain fracture toughness (K_{Ic}) as reported by the U.S. Steel Applied Research Laboratory, and (3) evaluate the concept of through-the-thickness yielding as an accept-reject criterion for steel procurement.

Background

Investigators at the U.S. Steel Applied Research Laboratory [1-6] have reported that static plane-strain K_{Ic} fracture toughness values correlate with:

(1) precrack Charpy slow-bend (PCSB) data,
(2) Charpy V-notch (CVN) impact data in the transition-temperature region,
(3) CVN impact data in the upper-shelf region,

and that dynamic plane-strain K_{Ic} fracture toughness values correlate with:

(1) precrack Charpy impact (PCI) values.

Rolfe and Gensamer[1] found that a K_{Ic}-CVN correlation exists for steels having yield strengths greater than 110 ksi when tested at plus 80°F, a temperature which produced full shear behavior in their steels.

Barsom and Rolfe[2] showed that a K_{Ic} temperature transition exists for A517-F steel that is independent of specimen thickness (Figure 1). In addition to K_{Ic} bend testing, standard Charpy V-notch (CVN) and precrack Charpy

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(1) S. T. Rolfe and M. Gensamer "Fracture-Toughness Requirements for Steels" AD 835 923L, 20 Sept. 1968.
(2) J. M. Barsom and S. T. Rolfe "K_{Ic} Transition-Temperature Behavior of A517-F Steel" AD 846 124L, 29 Nov. 1968, and ENGINEERING FRACTURE MECHANICS, 1971, Vol. 2, pp. 341-357.

slow-bend (PCSB) and impact (PCI) tests were made. From fractographic analysis, it was shown that in both the K_{Ic} tests and Charpy tests, the transition was associated with a change in fracture mode from quasicleavage at cryogenic temperature to dimpled rupture at room temperature. The plots of energy absorption, percent shear, and lateral expansion are shown in Figure 2. A 50°F increase in transition temperature was indicated as a result of the higher strain rate associated with impact as compared with slow bend (0.025 in./minute). The investigators also made the observation that the static plane-strain K_{Ic} transition temperature range was the same as that defined by fatigue-cracked slow-bend Charpy tests*.

A procedure was proposed by the U.S. Steel investigators for predicting the dynamic K_{Ic} behavior of a material by shifting static K_{Ic} test data along the temperature axis by the same amount as the static Charpy (PCSB) energy values are shifted by impact testing (PCI). Shoemaker and Rolfe[3] studied the effect of loading rate on the K_{Ic} of seven structural steels. The shift to higher temperature produced by impact loading when PCI and PCSB tests are compared is shown in Table 1. The results confirmed the general observation that low-strength steels are the most strain-rate sensitive. Dynamic K_{Ic} data were obtained by impacting strain-gaged 3-point bend specimens with a falling weight. It was shown that the dynamic K_{Ic} behavior of the various steels investigated could be predicted from static K_{Ic} data by adjusting the latter along the temperature axis by the amount that fatigue-precracked Charpy slow-bend (PCSB) and impact (PCI) data were displaced from one another (Figure 4).

Barsom and Rolfe[4] later confirmed the observation that the onset of the temperature transition for static (slow-bend) and dynamic K_{Ic} data occurs at about the same temperatures as the onset of the temperature transition for fatigue-cracked Charpy slow-bend and impact data, respectively. In discussing the observed correlations, Barsom and Rolfe point out that to attain such a

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*When Aerojet investigators compared the U.S. Steel data from static K_{Ic} and Charpy tests, the temperature transition for the static K_{Ic} and PCI tests appeared to nearly coincide (at approximately -120°F) inspite of the difference in rate of loading (Figure 3).

(3) A.K. Shoemaker and S.T. Rolfe, "The Static and Dynamic Low-Temperature Crack Toughness Performance of Seven Structural Steels", AD 846-126L, 29 Nov. 1968, and ENGINEERING FRACTURE MECHANICS, 1971, Vol. 2, pp. 319-339.

(4) J.M. Barsom and S.T. Rolfe, "Correlations Between K_{Ic} and Charpy V-Notch Test Results in the Transition-Temperature Range", IMPACT TESTING OF METALS, ASTM STP 466, 1970, pp. 281-302.

Table 1 - Increase in Transition Temperature as a Result of Impact Loading Steels of Various Yield Strengths (Ref. 3).

Steel	Yield Strength (ksi)	Shift in Transition Temperature (°F)
A36	37	160
ABS-C	39	140
A302B	56	130
HY-80	84	80
A517-F	118	60
HY-130	137	0
18 Ni (180)	180	0

correlation, the effects of both notch acuity and strain rate should be considered. Thus, the energy-absorption data obtained with slow bend fatigue-cracked Charpy (PCSB) specimens were compared with data obtained with slow-bend K_{Ic} specimens, and the data obtained with dynamic (impacted) fatigue-cracked Charpy (PCI) specimens were compared with dynamic K_{Ic} specimens. Figure 5 shows these comparisons; note that the empirical correlation between slow-bend K_{Ic} and PCSB test results is the same as that between dynamic K_{Ic} and PCI test results.

The U.S. Steel researchers[1,2,4,5] also investigated the possibility of empirical K_{Ic}-CVN correlations. In this connection, they pointed out that the most widely used tests (in screening and specifications for toughness) are the static K_{Ic} test and the standard Charpy V-notch (CVN) impact test. These two test specimens have different notch acuities and are tested at different loading rates. Nonetheless, because even approximate correlations would be useful to the materials engineer, test results for these specimens were compared. The empirical correlation, based on tests at +80°F which corresponded to the upper shelf in the CVN impact testing of the U.S. Steel materials and dimpled rupture in the static K_{Ic} specimens, is shown in Figure 6.

Gross[6] carried the correlation one step further. He combined the upper-shelf correlation of Barsom and Rolfe

$$(K_{Ic}/FTY)^2 = 5\ (CVN - FTY/20)/FTY \tag{1}$$

with an expression from the work of Hahn and Rosenfield[7]

$$K_{Ic} = FTY \cdot B^{1/2} \tag{2}$$

where K_{Ic} is the plane-strain stress intensity for through-thickness yielding. The combination of these expressions resulted in the following simplified equation:

$$CVN = FTY\ (B + 0.25)/5 \tag{3}$$

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(6) J.H. Gross, "Effect of Strength and Thickness on Notch Ductility", IMPACT TESTING OF METALS, ASTM STP-466, 1970, pp. 21-52.

(5) S.T. Rolfe and S.R. Novak "Slow-Bend K_{Ic} Testing of Medium-Strength High-Toughness Steels", REVIEW OF DEVELOPMENTS IN PLANE-STRAIN FRACTURE TOUGHNESS TESTING, ASTM STP 463, American Society for Testing and Materials, September 1970, pp. 124-159.

This is the concept of through-thickness yielding as a basis for establishing a minimum Charpy V-notch impact energy level.

In terms of linear-elastic fracture mechanics, the concept of through-thickness yielding is the same as saying that the crack-tip plastic zone must be equal to the thickness of the plate. Under plane-stress conditions, the plastic zone is estimated to be

$$r_p = (K_c/FTY)^2/2\pi = B \qquad (4)$$

and in plane strain

$$r_p = (K_{Ic}/FTY)^2/6\pi = B \qquad (5)$$

An expression suggested by Wells[8]

$$W/A = 4\pi \; FTY^2 \; B/E \qquad (6)$$

can be derived by substituting $EG_c = K_c^2$ in equation (4) and using the precrack Charpy W/A value as an approximation of G_c, i.e., $E(W/A) = K_c^2$. The coefficient of 4π in equation (6) appears to be a compromise between the 2π coefficient for plane stress (Equation 4) and 6π for plane strain (Equation 5). Gross[5] rejected equation (6) proposed by Wells as requiring unrealistically high Charpy values and used equation (2) as determined by Hahn and Rosenfield. If the plane-stress coefficient 2π had been used by Wells, equation (6) becomes

$$W/A = 2\pi \; FTY^2 \; B/E \qquad (7)$$

which is a less conservative expression than equation (6) but more conservative than equation as used by U.S. Steel. With through-thickness yielding, a plane-stress condition will prevail and, therefore, the 2π coefficient of equation (7) is the more realistic choice.

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(7) G.T. Hahn and S.R. Rosenfield, "Plastic Flow in the Locale of Notches and Cracks in Fe-3Si Steel under Conditions Approaching Plane Strain", Final Report SSC-191 on Ship Structure Committee Project SR-164, "Local Strain Movement", Nov 1968.

(8) A.A. Wells, "Fracture Control of Thick Steels for Pressure Vessels", The British Welding Journal, Vol. 15(5), 1958, p. 221.

Rolfe and Novak[6], using four-point bend-test specimens, addressed themselves to the problem of measuring toughness in medium-strength steels. All but one of the eleven steels investigated had yield strengths below 200 ksi, including A517-F at 110 ksi. For purposes of studying the limitations of linear-elastic fracture mechanics, a series of slow-bend K_{Ic} tests were conducted on several steels. Because their materials were limited to a maximum of 2-in. thickness, only five of the eleven steels investigated included tests which met the ASTM requirement that

$$B \geq 2.5\ (KQ/FTY)^2 \leq a$$

Furthermore, only six of the eleven steels met the ASTM bend requirement for specimen depth, viz.,

$$W \geq 5\ (KQ/FTY)^2$$

Thus, tests of five of the eleven steels, viz., A517-F(AM), 4147(AM), HY-130T(AM), and 12Ni-5Cr-3Mo(VM) in two heats, did not meet the ASTM Committee E-24 size requirements. Nevertheless, the data from all eleven steels conformed to the relationship of equation (1) as shown in Figure 6.

Begley and Toolin[9] confirmed the upper-shelf relationship by adding two valid data points from intermediate-strength NiCrMoV rotor steels. The upper-shelf K_{Ic} values for the NiCrMoV steels were in excellent agreement with the Rolfe-Novak upper-shelf correlation as shown in Figure 6 (see plotted squares). The Westinghouse investigators qualified the correlation as applying to materials not significantly strain-rate sensitive.

In addition to the upper-shelf relationship, Barsom and Rolfe[4] showed that an empirical correlation exists between standard CVN impact test data and static K_{Ic} on the low side of the transition-temperature range. The relationship, based on data from five steels (ABS-C, A302-B, A517-F, HY-130 and 18Ni-250, is given by

$$K_{Ic}^2/E = 2(CVN)^{3/2} \tag{8}$$

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(9) J.A. Begley and P.R. Toolin, "Fracture Toughness and Fatigue Crack Growth Rate Properties of a NiCrMoV Steel Sensitive to Temper Embrittlement" presented at the Fourth National Symposium on Fracture Mechanics, Carnegie Mellon University, Pittsburgh, Pa., August 1970.

The slow-bend K_{Ic} tests for these steels were conducted in the transition region and satisfied the ASTM E-24 requirements for K_{Ic} testing. However, the data used to establish the relationship exhibited considerable scatter (as compared with Figure 6).

Corten and Sailors[10] using pressure-vessel steels such as A533-B and A517-F established a different correlation, indicating the following empirical relation

$$K_{Ic} = 15.5(CVN)^{1/2} \tag{9}$$

which is numerically equivalent to

$$K_{Ic}^{2}/E = 8(CVN) \tag{10}$$

They found the above expressions to provide a good empirical representation of the relation between static K_{Ic} and CVN impact for thick-section steels in the range of 5 to 50 ft-lb as measured in the transition-temperature range. Corten and Sailors found the relation by Barsom and Rolfe to underestimate K_{Ic} at low values of CVN and overestimate K_{Ic} at higher values of CVN.

PROCEDURE

Materials

The materials selected for study are listed in Table 2. The basis for selection was a wide range of nil-ductility transition (NDT) temperatures as indicated by the precrack Charpy impact (PCI) test.

Tension tests (0.505-in. dia) were conducted at temperatures encompassing the transition temperature range as indicated by PCI tests. The test results are shown in Table 3 and are plotted in Figures 7, 8 and 9.

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(10) H.T. Corten and R.H. Sailors, "Relationship Between Material Fracture Toughness Using Fracture Mechanics and Transition Temperature Tests", University of Illinois Department of Theoretical and Applied Mechanics, Report No. 346, August 1971 (UCCND subcontract 3398 for Oak Ridge National Laboratory).

Table 2 - Materials Investigated

ASTM Spec.	Plate No.	Code	Thickness	Source	Heat No.	Estimated NDT (°F)
A514-F	M	(ZU)	2-1/2	U.S. Steel	92L088-10W2	-90
	L	(ZV)	2-1/4	U.S. Steel	97L168-06W2	-20
A517-F	A	(ZW)	2-1/4	Lukens	B9893-2C	+40
A514-H	R	(ZX)	2	U.S. Steel	07919-03W1	-40
A517-H	Z	(ZT)	2-1/4	Lukens	B9093-4B	-10
	AL	(ZY)	2-1/4	Lukens	A4071-6	+60
	Q	(ZZ)	2-1/4	Lukens	C4913-4	> 200

Table 3 - Tensile Strength (0.505-in. dia) and Ductility as a Function of Temperature

ASTM Spec	Plate No.	Spec. Code	Test Temp. (°F)	Yield Stress (ksi)	Ult. Stress (ksi)	Elong. (%)	R.A. (%)
A514-F	M	ZU	-320	176.2	176.5	22.8	52
			-100	123.1	135.0	23.4	64
			-20	120.6	130.6	21.8	67
	L	ZV	-100	117.8	130.3	23.0	67
			-30	112.8	126.1	23.0	65
			+40	110.6	122.1	22.7	67
A517-F	A	ZW	-80	112.6	128.8	20.5	58
			+40	107.6	122.1	20.4	60
			+160	101.8	115.6	19.6	61
A514-H	R	ZX	-100	122.1	134.8	20.6	58
			-14	116.8	129.1	19.9	62
			RT	113.8	123.8	19.0	62
A517-H	Z	ZT	-100	124.8	139.3	21.5	59
			-40	121.8	135.3	20.9	61
			+20	119.8	132.3	20.3	61
	AL	ZY	-80	107.8	126.3	20.6	57
			+40	104.8	120.3	19.5	57
			+160	100.3	114.6	18.9	58
	Q	ZZ	-40	118.1	134.3	16.7	44
			RT	111.8	126.8	16.7	49
			+210	108.8	121.8	15.7	47

Charpy Impact Testing

The standard Charpy V-notch (CVN) impact specimen was machined and tested in accord with ASTM E23-66.

The precrack Charpy impact (PCI) test is not an ASTM standard test; however, its development as a research test method dates back to the mid 1950's[(11-16)]. In the last decade it has been put into increasing use because it is consistent with the fracture mechanics concept of testing with a natural crack, and, like the standard Charpy V-notch impact specimen, it is highly sensitive to metallurgical variables affecting fracture toughness and economical in terms of the amount of material required, the low cost of machining and the ease of testing over a wide range of temperature.

Contrary to the observation of some investigators, one cannot count on a uniform displacement between the CVN and PCI transition curves. In some materials, the displacement between the curves can vary from 40 to 100°F from heat to heat in a given composition type. In that the PCI test with a natural crack can be expected to indicate the higher transition temperature, the PCI test was used as a qualitative test for screening the steels of this investigation and as a basis for comparison with the static K_{Ic} tests.

Compact Tension Testing

A tentative test method for determining the plane-strain fracture toughness of metallic materials is included in ASTM Standards (E399-70T) effective 19 March 1970. The test method includes both bend and compact tension; the compact tension specimen was used in this study. Figure 10 shows the 2-in.-thick specimen.

The specimens were fatigue precracked in a Wiedemann (Satec) Model SF 10U Fatigue Machine which is load controlled and operates at 1800 cpm. With this system, a static load of 10 percent of the maximum fatigue load was applied, and the fatigue cycling was done between the specified maximum and the static load. Specimens ZTD, ZUD, ZVD, ZWD, ZXD and ZZD (one 1-in.-thick specimen from each of the steels not previously tested) provided preliminary test data to determine the approximate critical stress intensity of each steel and to

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(11) C.E. Hartbower, "Crack Initiation and Propagation in V-Notch Charpy Impact" ASTM PROCEEDINGS, Vol. 56 (1956), p. 521; also WELDING JOURNAL, Vol. 36(11), p. 494-s, Nov. 1957.

(12) G.M. Orner and C.E. Hartbower, "Effect of Specimen Geometry on Charpy Low-Blow Transition Temperature", WELDING JOURNAL, Vol. 36(12), p. 521-s, Dec. 1957.

determine if the stress intensity used in fatigue cracking complied with the requirements of ASTM E399. These specimens were tested at the lowest temperature anticipated in the test program.

The stress intensity for fatigue cracking the six specimens conformed to ASTM E399 with the exception of ZTD. Based on the test results for the six specimens, adjustments were made in the loads for fatigue cracking the balance of the specimens.

For the low-temperature testing, the 1-inch thick specimens were submerged in a mixture of methyl alcohol and dry ice for test temperatures between minus 100 and plus 40°F; liquid nitrogen (LN_2) was used for testing at -320°F. A Checktronic Corporation temperature-controlled chamber was used for elevated temperature testing both the 1-inch and 2-inch thick specimens, as well as for cryogenic testing the 2-inch-thick specimen at temperatures below minus 40° and the 1-inch-thick specimens at temperatures below minus 100°F. A thermometer was used to monitor the temperature of the methyl alcohol and a thermocouple was used for monitoring temperature in the chamber. The thermocouple was placed in the machined notch of each specimen, out of the direct path of the circulating air.

The specimens were tested in a Wiedemann Baldwin 60,000 lbs. machine using a manual-controlled load rate. The desired load rate was obtained by adjusting the load rate so the load-indicating pointer followed a moving circular dial, preset to the desired rate.

A crack-opening displacement gage (Figure 11) was used for determining the load (P_q) for calculating the plane-strain critical stress intensity. The gage was positioned so as to bridge the specimen preflaw by inserting the gage between knife edges machined into the face of the specimen at the end of the notch. The particular crack-opening-displacement gage employed has been developed specifically for pop-in and slow-crack-growth measurements where very small changes in compliance are anticipated. The gage consists of a full bridge of electric resistance strain gages mounted on a double cantilever beam with the amount of flexure in the cantilever arms controlled by the thickness of the spacer between the arms at the base of the cantilever.

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(13) G.M. Orner and C.E. Hartbower, "The Low-Blow Transition Temperature", ASTM PROCEEDINGS, Vol. 58 (1958), p. 623.
(14) G.M. Orner and C.E. Hartbower, "An Engineering Evaluation of Notch Sensitivity in High-Strength Sheet", WELDING JOURNAL, Vol. 39(4), p. 147-s, April 1960.

Computer Program

The compact-tension test results were evaluated by ASPC Univac 1108 computer program SA 017 dated 1/72. An example of the computer printout is shown in Table 4; the following data were input to the computer:

a. specimen identification and test temperature
b. specimen thickness, B
c. yield strength, FTY
   at room temperature, FTY
   at test temperature, FTYTT
d. specimen overall length, LENT
e. hole diameter, DIA
f. edge of hole to end of specimen, LENH
g. crack measurements, A
   (1) machined chevron notch, A1
   (2) fatigue crack at free surface, A2
   (3) fatigue crack at 1/4-point, A3
   (4) fatigue crack at mid-thick., A4
   (5) fatigue crack at 1/4-point, A5
   (6) fatigue crack at free surface, A6
   (7) machined chevron notch, A7
h. load values, P
   (1) secant load, PQ
   (2) load at failure, PFAIL
   (3) load for initial increment of fatigue, PIF
   (4) load for final increment of fatigue, PFF
   (5) loading rate, PLR
i. fatigue crack increment, DELA
j. Young's modulus, YMOD

The computer printout includes, in addition to the critical stress-intensity value K(Q), the following parameters specified by ASTM E399-72 to test the validity of the measured stress-intensity value:

A(AVG)/W	ratio of average crack length to specimen depth shall be 0.45 to 0.55 (ref ASTM E399 par. 7.3.3)
.05*A(AVG)	5 percent of the crack length (see par. 7.2.3 and 8.2.3)
MAX ABSOLUTE DIFFERENCE	the difference between any of the crack length measurements shall not exceed 5% of the average (see par. 8.2.3)
MINIMUM ABS. DIFF.	no part of the crack front shall be closer to the machined notch root than 5% (see par. 8.2.3).

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(15) G.M. Orner and C.E. Hartbower, "Sheet Fracture Toughness Evaluated by Charpy Impact and Slow Bend", Ibid., Vol. 40(9), p. 405-s, Sept. 1961.
(16) G.M. Orner and C.E. Hartbower, "Transition Temperature Correlations in Constructional Alloy Steels", Ibid., p. 459-s, October 1961.

TABLE 4. COMPACT-TENSION PROGRAM, DEPT 4350, 1/72 SA017

SPECIMEN ZVC AT MINUS 100F

```
        INPUT FOLLOWS...
$OUT
A        =     .27510000E+01      .29080000E+01      .29900000E+01,
 .30170000E+01,     .30070000E+01,     .29450000E+01,     .27550000E+01,
B        =     .20030000E+01
DELA     =     .21000000E+00
DIA      =     .10000000E+01
LENH     =     .49900000E+00
LENT     +     .50010000E+01
FTY      =     .10980000E+03
FTYTT    =     .11700000E+03
PFAIL    =     .30950000E+02
PFF      =     .11000000E+02
PIF      =     .16000000E+02
PLR      =     .30000000E+02
PQ       =     .30950000E+02
YMOD     =     .30000000E+05
$END
```

A(AVG)	2.00567
A(AVG)/W	.50117
K(Q)	74.43505
K(IF)	33.17530
.6*K(Q)	41.91266
K(FF)	26.45511
1.2E-3*YMOD	33.78461
K(LR)	72.15029
B(THEO)	1.01187
MAX ABS A3-A4	.02700
.05*A(AVG)	.10028
MIN ABS A2-A1	.15700
A2/A(AVG)	.95180
A6/A(AVG)	.97025
PQ/P(FAIL)	1.00000

A2/A(AVG) and/or A6/A(AVG)	the length of crack at the free surface shall not be less than 90% of the average crack length (ref par. 8.2.3)
1.2E-3*YMOD	the ratio of the maximum stress intensity used in the final stage of fatigue precracking to Young's modulus shall not exceed 0.002 in.$^{1/2}$ (ref par. 7.4.2).
.6*K(Q)	6 percent of the measured stress intensity.
K(FF)	the max. stress intensity in fatigue precracking shall not exceed 60 percent of the measured KQ value (ref par. 7.4.2).
K(LR)	specimens shall be loaded at a rate such that the stress intensity increases at a rate within the range of 30 to 150 ksi-in.$^{1/2}$ per minute (ref par. 8.4).
B(THEO)	2.5 $(KQ/FTY)^2$ shall be less than the thickness (B) and less than the crack length (A) (ref par. 9.1.5).
PQ/P(FAIL)	the ratio of max. load to load at failure shall not exceed 1.10 (ref par. 9.1.2).

TEST RESULTS

Charpy Test Results

The plots of Charpy impact energy (ft-lb) versus test temperature (°F) for the seven steels are shown in Figures 12 through 18. Note that the PCI test had the characteristic of a well-defined inflection point (intersection of two straight lines) which has been shown previously to provide an approximation of the NDT temperature[17].

The well-defined change in the slope of the curve relating precrack Charpy energy and test temperature is substantiated by lateral expansion measurements. Figure 19 illustrates this in precrack Charpy impact (PCI) test results from Plate A (A517-F). A direct proportionality between energy and lateral expansion has been reported previously[18-20]. Figure 20 is a plot of

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(17) WELDING HANDBOOK, Section 1, 5th Edition, Table 6.3, American Welding Society, New York.

(18) C.E. Hartbower and W.S. Pellini, "Mechanical and Material Variables Affecting Correlation", THE WELDING JOURNAL, Vol. 29(7), p. 347-s, Figure 15, July 1950.

standard Charpy V-notch (CVN) and precrack Charpy impact (PCI) versus lateral expansion measurements. The change in slope shown in the precrack Charpy plot of energy versus lateral expansion was previously observed by Orner[21].

The temperatures corresponding to the inflection points in the PCI energy-versus-temperature plots are reported in Table 5. Note that the transition temperatures ranged from minus 90°F for U.S. Steel plate M to over plus 200°F for Lukens' plate Q.

Table 5. Approximate Nil-Ductility Transition (NDT) Temperatures Based on Precrack Charpy Impact Tests

Steel	NDT (°F)
M	-90
R	-40
L	-20
Z	-10
A	+40
AL	+60
Q	> +200

Compact Tension Test Results

The data obtained from the 1-in.-thick compact tension tests are shown in Table 6, and the data from the 2-in.-thick compact-tension tests are shown in Table 7. Note that at the higher test temperatures, ASTM E399 test requirements for thickness and crack depth

$$B \geq 2.5\ (KQ/FTY)^2 \leq a$$

were violated in a number of tests because of the program requirement to test at temperatures above the transition range.

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(19) C.E. Hartbower, "The Poisson Effect in the Charpy Test", ASTM PROCEEDINGS, Vol. 54 (1954), p. 929.

(20) J.H. Gross and R.D. Stout, "Ductility and Energy Relations in Charpy Tests of Structural Steels", THE WELDING JOURNAL, Vol. 37(4), p. 151-s, April 1958.

(21) G.M. Orner, "Charpy Brittle-Fracture Transitions by the Lateral Expansion Energy Relationship", THE WELDING JOURNAL, Vol. 37(5), p. 201-s, May 1958.

Table 6. Summary of One-Inch-Thick Compact-Tension Test Results

Plate Designation, Material Spec. Heat Number	Specimen No.	Test Temp. (°F)	Fatigue Final K (ksi-in.$^{1/2}$)	Crack Depth Avg.(in.)	Failure Secant PQ(kips)	Load Maximum (kips)	Ratio A/W	Critical Stress Intensity (ksi-in.$^{1/2}$)	Valid Min. Thick. (in.)
Plate L (2-1/4-in.) A514F (U.S. Steel) Heat 97L168-06W2	ZVE	-200	33.1	1.054	6.57	6.57	0.526	48.3	0.34
	ZVI	-150	29.6	0.980	8.69	8.69	0.490	57.2	0.55
	ZVG	-130	26.3	0.946	9.78	9.78	0.472	61.2	0.66
	ZVD	- 80	27.6	0.979	9.25	11.60	0.489	60.7	0.68
	ZVF	- 40	27.7	0.982	14.45	14.45	0.490	95.2	1.77
	ZVH	0	28.7	1.006	15.60	18.00	0.502	106.5	2.28
Plate M (2-1/4-in.) A514F (U.S. Steel) Heat 92L088-10W2	ZUE	-320	33.8	0.973	6.65	6.65	0.485	43.2	0.015
	ZUG	-210	28.3	0.949	11.45	11.45	0.474	72.0	0.70
	ZUF	-140	27.3	0.972	16.10	16.10	0.485	104.6	1.69
	ZUH	-103	27.6	0.980	15.30	18.30	0.489	100.6	1.65
	ZUD	- 80	27.6	0.981	18.00	24.00	0.490	118.4	2.34
	ZUI	- 40	29.4	0.978	15.50	23.05	0.489	101.5	1.79
Plate A (2-1/4-in.) A517F (Lukens) Heat B9893-2C	ZWG	-200	30.8	1.051	7.40	7.40	0.525	54.3	0.46
	ZWI	-102	31.4	1.020	16.60	17.15	0.509	115.8	2.58
	ZWH	- 39	30.8	1.008	15.20	21.55	0.503	104.1	2.20
	ZWD	- 2	31.0	1.056	13.50	18.70	0.527	99.6	2.09
	ZWE	+ 39	36.4	1.023	13.25	20.15	0.511	92.9	1.86
	ZWF	+ 75	29.5	1.024	15.75	20.10	0.511	110.6	2.72
Plate R (2-in.) A514H (U.S. Steel) Heat 07619-03W1	ZXH	-210	28.1	0.992	8.34	8.34	0.495	55.8	0.43
	ZXF	-151	28.7	0.959	6.55	6.55	0.479	41.8	0.27
	ZXE	-102	28.8	0.962	9.92	9.92	0.480	63.5	0.68
	ZXD	- 80	27.6	0.980	8.05	8.05	0.489	52.9	0.48
	ZXG	0	27.5	0.979	12.00	12.00	0.488	78.7	1.15
	ZXI	+ 76	36.4	1.020	13.72	13.90	0.510	95.9	1.78
Plate Z (2-1/4-in.) A517H (Lukens) Heat B9093-4B	ZTG	-205	30.6	1.048	5.02	5.14	0.523	36.6	0.18
	ZTD	-144	33.4	1.131	5.60	5.60	0.564	48.8	0.33
	ZTF	- 79	31.1	1.058	7.70	7.70	0.528	57.0	0.53
	ZTH	- 40	30.0	1.035	9.75	9.75	0.517	69.7	0.82
	ZTE	+ 20	30.7	1.050	12.55	12.55	0.524	91.8	1.47
	ZTI	+ 72	30.2	1.040	15.35	15.35	0.519	110.5	2.17
Plate AL (2-1/4-in.) A517H (Lukens) Heat A4071-6	ZYD	-102	33.3	1.057	6.54	6.54	0.527	48.3	0.49
	ZYH	-101	33.6	1.063	6.85	6.85	0.531	51.1	0.54
	ZYF	- 39	33.8	1.065	7.64	7.64	0.532	57.4	0.72
	ZYI	0	33.9	1.069	7.96	7.96	0.534	60.0	0.81
	ZYE	+ 40	32.9	1.050	10.30	10.30	0.524	75.4	1.29
	ZYG	+120	33.4	1.059	12.52	13.75	0.528	92.8	2.07
Plate Q (2-1/4-in.) A517H (Lukens) Heat C4913-4	ZZI	0	27.5	0.979	7.35	7.35	0.488	48.2	0.40
	ZZE	0	24.8	0.904	7.76	7.76	0.452	45.9	0.40
	ZZD	+ 40	28.0	1.023	7.35	7.93	0.511	51.5	0.52
	ZZH	+ 75	27.8	1.020	8.29	8.29	0.509	57.7	0.67
	ZZF	+159	27.6	0.980	9.12	9.85	0.489	59.9	0.75
	ZZG	+200	26.0	0.973	9.82	10.30	0.485	63.8	0.86

Table 7. Summary of Two-Inch-Thick Compact-Tension Test Results

Plate Designation, Material Spec. Heat Number	Specimen No.	Test Temp. (°F)	Fatigue Final K (ksi-in.$^{1/2}$)	Crack Depth Avg.(in.)	Failure Secant PQ(kips)	Load Maximum (kips)	Ratio A/W	Critical Stress Intensity (ksi-in.$^{1/2}$)	Valid Min. Thick. (in.)
Plate L (2-1/4-in.)	ZVC	-100	26.4	2.006	30.95	30.95	0.501	74.4	1.01
A514F (U.S. Steel)	ZVB	- 55	26.3	1.998	47.70	47.70	0.500	114.2	2.46
Heat 97L168-06W2	ZVA	75	26.2	1.987	52.8	>59.75	0.497	125.7	3.27
Plate M (2-1/4-in.)	ZUC	-250	26.5	2.008	16.70	16.70	0.502	40.26	0.18
A514F (U.S. Steel)	ZUA	-100	26.4	2.002	44.95	44.95	0.500	107.84	1.89
Heat 92L088-10W2	ZUB	+ 75	26.7	2.018	51.50	59.80	0.504	125.16	2.86
Plate A (2-1/4-in.)	ZWA	-250	30.8	2.196	17.05	17.05	0.549	47.74	0.32
A517F (Lukens)	ZWC	-181	31.2	2.212	27.80	27.80	0.553	78.94	1.01
Heat B9893-2C	ZWB	-150	31.0	2.205	35.00	35.00	0.551	98.70	1.69
Plate R (2-in.)	ZXB	-200	27.7	2.064	14.88	14.88	0.516	37.46	0.19
A514H (U.S. Steel)	ZXC	- 50	26.0	1.981	26.35	26.35	0.495	62.32	0.68
Heat 07619-03W1	ZXA	+ 75	26.3	1.998	42.50	43.40	0.499	101.66	1.99
Plate Z (2-1/4-in.)	ZTA	-155	29.3	2.134	16.90	16.90	0.533	44.98	0.30
A517H (Lukens)	ZTC	-100	31.1	2.204	20.00	20.00	0.551	56.32	0.51
Heat B9093-4B	ZTB	+ 76	30.6	2.188	46.40	48.10	0.547	129.06	2.96
Plate AL (2-1/4-in.)	ZYC	-150	33.3	2.285	11.20	13.20	0.571	33.91	0.22
A517H (Lukens)	ZYA	-150	34.2	2.313	12.95	12.95	0.578	40.24	0.32
Heat A4071-6	ZYB	+ 75	37.2	2.402	25.00	31.30	0.600	84.61	1.68
Plate Q (2-1/4-in.)	CT1	+ 58	29.2	2.021	23.22	23.22	0.505	56.53	0.54
A517H (Lukens)	CT2	+ 58	29.3	2.025	21.95	23.30	0.506	53.66	0.49
Heat C4913-4	CT3	+ 58	29.7	2.041	22.05	22.75	0.510	54.59	0.50
	CT9	+ 75	30.0	2.052	22.50	22.50	0.513	56.24	0.63
	CT5	+113	29.7	2.039	23.65	23.90	0.510	58.45	0.60
	CT7	+113	30.0	2.052	23.30	24.50	0.513	58.24	0.59
	CT8	+113	29.3	2.025	24.25	24.85	0.506	59.25	0.61

The plots of KQ versus test temperature for the seven steels are shown in Figures 21 through 27 together with the PCI curves for each steel. Note that the static KQ curves were markedly displaced with respect to temperature as compared with the PCI curves. The displacement is attributed to a rate-of-loading effect. Note that the steels varied in this displacement and that the extent of the displacement as shown in Table 8, was much greater in plates A and M than the 60°F shift in A517-F heat 73A377 as reported by the U.S. Steel investigators (see Table 1).

Behavior in the A517-F heat (Plate A) was anomalous in that the K_{Ic} transition-temperature region (-200°F to -120°F) was followed by decreasing KQ values in the upper shelf (between -120 and +40°F).

<u>ASTM E399 Fatigue and Specimen-Size Limitations</u>. The ASTM test method for plane-strain fracture-toughness testing limits the non-uniformity of crack (fatigue precrack) fronts; viz., (1) the maximum irregularity in the crack envelope shall not exceed 5 percent of the average crack depth, (2) the crack extension shall be at least 5 percent of the average crack depth or 0.050-in. whichever is the greater measurement, and (3) the crack extension at the free surfaces shall be at least 90 percent of the average crack depth; furthermore, the specification limits the maximum stress intensity used in the final stage of the fatigue precracking operation. When these limits were exceeded, there was little or no effect on the measured stress intensity values based on comparisons between specimens fully in accord with E399 requirements and those with one or more irregularities.

A common discrepancy in specimens tested above the transition temperature was that the toughness was too great for the crack length and specimen thickness requirement; i.e., several of the test results were invalid because the thickness (B) and crack length (A) were less than 2.5 $(KQ/FTY)^2$. There has been some controversy regarding this requirement; some feel that it may be too conservative[22] and others that it may be too liberal[23]. In the current investigation, a number of tests were run above the transition-temperature range to establish the upper shelf of the transition curve. Some 1-in. and 2-in. compact tension tests were run at a common temperature which permitted observations on size effect. Table 9

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(22) W.G. Reuter and F.J. Flens, "Effect of Thickness on 7039-T63 Aluminum Alloy Plane-Strain Fracture Toughness", unpublished data from NERVA program.

(23) M.H. Jones and W.F. Brown, Jr., "The Influence of Crack Length and Thickness in Plane Strain Toughness Tests", REVIEW OF DEVELOPMENTS IN PLANE STRAIN FRACTURE TOUGHNESS TESTING, ASTM STP 463, American Society for Testing and Materials, 1970, pp. 63-101. Also W.F. Brown, Jr., and J.E. Srawley, "Commentary on Present Practice" <u>loc. cit</u> pp. 216-248.

TABLE 8. TRANSITION-TEMPERATURE SHIFT DUE TO RATE OF LOADING (Static K_{Ic} vs PCI)

Type	Plate	Transition Temperature Precrack Charpy Impact (°F)	Transition Temperature Compact Tension Static (°F)	Shift ΔT (°F)
A514F	M(ZU)	-90	-250	160
	L(ZV)	-20	-100	80
A517F	A(ZW)	+40	-200	240
A514H	R(ZX)	-40	-120	80
A517H	Z(ZT)	-10	- 60	50
	AL(ZY)	+60	0	60
	Q(ZZ)		Undetermined	

TABLE 9. SIZE EFFECT IN COMPACT TENSION TESTS

Specimen	Thick.	Temp.	PFAIL/PQ*	KQ	$2.5\ (KQ/FTY^2)$
ZUH	1.0	-103	1.20	100.6	1.65
ZUA	2.0	-100	1.00	107.8	1.89 (valid)
ZXI	1.0	76	1.01	95.9	1.78
ZXA	2.0	75	1.02	101.7	1.99 (valid)
ZVF	1.0	-40	1.00	95.2	1.77
ZVB	2.0	-55	1.00	114.2	2.46
ZTI	1.0	72	1.00	110.5	2.17
ZTB	2.0	76	1.04	129.1	2.96

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*As an added assurance of valid test data, it has been proposed(24) that the ratio P_{max}/PQ be limited to some value less than 1.10. The reason for this is to limit the amount of crack-tip plasticity contributing to PQ.

(24) W. F. Brown, Jr., and J. E. Srawley, "Commentary on Present Practice" STP 463, p. 221.

lists these data; note that in the case of 2-in.-thick specimens ZUA and ZXA (both valid tests), the K_{Ic} values were somewhat higher than the companion invalid 1-in.-thick KQ values. Fictitiously low values are expected from undersize specimens. In the case of 2-in.-thick specimens ZVB and ZTB, with toughness too high for valid testing in 2-inches, the trend was the same, with higher K_{Ic} values obtained from the 2-in. than from the 1-in.-thick specimens.

Upper Shelf K_{Ic}-CVN Correlation

U.S. Steel has reported an empirical correlation between standard Charpy V-notch (CVN) impact energy absorption values measured at the upper shelf and static K_{Ic} values. The relationship was based on several steels having room-temperature yield strengths ranging from 39 to 246 ksi, and room-temperature bend-test critical-stress-intensity values ranging from 87 to 246 ksi-in.$^{1/2}$ (see Equation 1 and Figure 6).

One of the steels used by the U.S. Steel investigators in establishing the correlation was A517-F heat 73A377; for this heat the upper-shelf CVN energy was 62 ft-lb at 80°F and the KQ value as determined by 2 x 6-in. cross-section bend specimens was 170 ksi-in.$^{1/2}$. All tests were conducted at 80°F; at this temperature, the CVN impact values were reported to be "shelf" values in that all specimens exhibited 100 percent fibrous fracture. The plane-strain fracture toughness test results for the A517-F heat investigated by U.S. Steel are shown in Table 10. From this tabulation, it will be seen that the three tests did not satisfy the ASTM specimen-size requirements. Nevertheless, the U.S. Steel A517-F data complied with the relationship

$$(K_{Ic}/FTY)^2 = 5(CVN-FTY/20)/FTY \qquad (1)$$

where K_{Ic} was the static value of fracture toughness at 80°F in units of ksi-in.$^{1/2}$.

Of the A514/517 heats investigated in this study, only A514-F plates L and M developed upper-shelf CVN energy values at 80°F or lower temperature. Therefore, for purposes of calculating K_{Ic} values based on upper-shelf CVN impact test results, it was necessary to use CVN values obtained at temperatures higher than 80°F. Table 11 shows the calculated K_{Ic} values at the upper-shelf test temperatures; note that the calculated values were considerably higher than the measured values at the highest temperature investigated in this study.

TABLE 10. U.S. STEEL PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR A517-F HEAT 73A377*

THICKNESS			CRACK DEPTH		
B	$B/(KQ/FTY)^2$	$2.5(KQ/FTY)^2$	a	$a/(KQ/FTY)^2$	$2.5(KQ/FTY)^2$
1.84	0.71	6.48	2.60	1.01	6.44
1.85	0.87	5.32	2.55	1.20	5.31
1.85	0.69	6.70	1.78	0.67	6.64

BEAM DEPTH			KQ MEASUREMENT	
W	$W/(KQ/FTY)^2$	$5(KQ/FTY)^2$	10% Secant	Pop-in
6.0	2.32	12.93	177	177
6.0	2.83	10.60	160	-
6.0	2.24	13.39	175	180

---

*Under the provisions of ASTM E399, it is required that both the crack depth (a) and the specimen thickness (B) must be at least $2.5\ (KQ/FTY)^2$, and the beam depth (W) must be twice the specimen thickness, i.e., $W > 5(KQ/FTY)^2$. The data in this table are from reference 5.

TABLE 11. PLANE-STRAIN FRACTURE TOUGHNESS CALCULATED FROM CHARPY V-NOTCH UPPER SHELF ENERGY

$$(K_{Ic}/FTY)^2 = 5(CVN-FTY/20)/FTY$$

Plate/Code	Charpy V-Notch (CVN) Shelf (ft-lb)	Charpy V-Notch (CVN) Shelf (°F)	At Shelf Temperature Yield (ksi)	At Shelf Temperature CVN/FTY (ft-lb/ksi)	$(K_{Ic}/FTY)^2$ (from Fig. 6) (inch)	K_{Ic} @ Shelf Temperature (ksi-in.$^{1/2}$)
A/ZW	40	+200(a)	100	0.40	1.75	132
AL/ZY	42	+200(a)	98	0.43	1.90	135
L/ZV	79	+60	110	0.72	3.35	200
M/ZU	65	0	119	0.55	2.50	190
Q/ZZ	23	+300(a)	107	0.21	0.82	97
R/ZX	56	+200(a)	110	0.51	2.30	167
Z/ZT	55	+200	112	0.49	2.20	166

(a) Shelf may be at a higher temperature and, therefore, the shelf energy value may be somewhat higher than indicated.

If the Charpy upper shelf occurs at a temperature higher than the lowest temperature anticipated in service, the calculated value of K_{Ic} based on the CVN-K_{Ic} upper-shelf correlation is meaningless in terms of the plane-strain fracture toughness at the lowest-anticipated-service temperature. Figure 28 illustrates this situation. For plate AL, the calculated K_{Ic} was 135 ksi-in.$^{1/2}$ at plus 200°F; whereas, the measured K_{Ic} at 0°F was only 60 ksi-in.$^{1/2}$. In the case of plate M, on the other hand, where the CVN upper shelf occurred at (or below) the lowest anticipated service temperature, the calculated K_{Ic} value of 190 ksi-in.$^{1/2}$ was deemed to be meaningful in terms of service. The fact that a 2-in. compact-tension specimen of plate M tested at 75°F indicated a critical stress intensity value of only 125 ksi-in.$^{1/2}$ (see Table 7) is further confirmation of fictitiously low critical stress intensity values when the material thickness is inadequate to meet the ASTM 2.5 $(KQ/FTY)^2$ criterion.

Lower Shelf K_{Ic}-PCI Correlation

Based on standard Charpy V-notch (CVN) impact values from the transition range and lower shelf of the Charpy transition curve, U.S. Steel investigators reported the following correlation:

$$K_{Ic}^{2}/E = 2\ (CVN)^{3/2} \qquad (8)$$

Charpy V-notch (CVN) impact and static K_{Ic} data from the A517-F, A514-F and A517-H steels of the current investigation were plotted to determine if they conformed to the above K_{Ic}-CVN relationship. The expression obtained by Corten and Sailors[10] was also examined. From Figure 29, it will be seen that the U.S. Steel relationship appeared to fit the data but there was considerable scatter in the rest results. Table 12 presents the data plotted in Figure 29, including tests made by U.S. Steel and those of the current investigation. Only valid K_{Ic} values were plotted. When all the data were considered, it was observed that the data from steels A and M produced the greatest scatter. These steels were the most strain-rate sensitive of the nine heats plotted (including two A517-F heats from the U.S. Steel investigations). From severely strain-rate sensitive plates A and M, the CVN impact values were much lower than would be expected based on the static KQ test results; thus,

TABLE 12. LOWER-SHELF K_{Ic}-PCI CORRELATION

Type	Specimen	PLANE-STRAIN FRACTURE TOUGHNESS TEST RESULT: Temp. (°F)	Size (in.)	$2.5\,(KQ/FTY)^2$ (in.)	KQ (ksi-in.$^{1/2}$)	KQ^2/E (psi-in.)	$(KQ/FTY)^2$ (in.)	CHARPY IMPACT: CVN (ft-lb)	PCI (ft-lb)	NDT[c] (°F)
A514F	M(ZU) A	-100	2	1.890	108 (a)	388	0.756	24	10.5	-90
	H	-103	1	1.645	101	340	0.658	23	10.5	
	D	- 80	1	2.344	118	464	0.938	32	14	
	I	- 40	1	1.790	102	347	0.716	51.5	32.5	
	B	+ 75	2	2.860	125	521	1.144	66.5(a)	52	
	L(ZV) C	-100	2	1.012	74	182	0.405	-	4	-20
	D	- 80	1	0.685	61	124	0.274	10	6.5	
	B	- 55	2	2.464	114	433	0.986	28.5	10.5	
	F	- 40	1	1.773	95 (a)	301	0.709	39.5	13	
	H	0	1	2.280	106	375	0.912	67	22.5	
	A	+ 75	2	3.270	126	529	1.308	79 (a)	47	
A517F	A(ZW) H	- 39	1	2.201	104 (a)	361	0.880	14	2	+40
	D	- 2	1	2.089	100	333	0.836	15	2.5	
	E	+ 39	1	1.863	93	288	0.745	18	4	
	F	+ 75	1	2.721	111	411	1.09	18.5	7.5	
A514H	R(ZX) E	-102	1	0.676	64	136	0.270	4.5	2.5	-40
	D	- 80	1	0.482	53	94	0.193	6.5	3	
	C	- 50	2	0.686	62	128	0.274	9	4.5	
	G	0	1	1.150	79	208	0.460	17.5	10	
	A	+ 75	2	1.995	102	356	0.798	34	19.5	
	Z(ZT) C	-100	2	0.507	56	104	0.203	7.5	3.5	-10
	F	- 79	1	0.533	57	108	0.213	8.5	4.5	
	H	- 40	1	0.817	70	163	0.327	13	6.0	
	E	+ 20	1	1.466	92	282	0.486	25	12	
	B	+ 76	2	2.965	129	554	1.186	36.5	21	
	I	+ 72	1	2.170	110	367	0.868	36	20	
A517H	AL(ZY)D	-102	1	0.487	48	77	0.195	-	1.5	+60
	F	- 30	1	0.721	57	108	0.288	7	5	
	I	- 0	1	0.809	60	120	0.324	10.5	6.5	
	E	+ 40	1	1.293	75	187	0.517	15	8.5	
	B	+ 75	2	1.677	85	241	0.671	21.5	12	
	G	+120	1	2.071	93	288	0.828	28	19	
	Q(ZZ) I	0	1	0.398	48	77	0.159	4	2.5	200
	D	+ 40	1	0.520	52	90	0.208	5.5	4	
	CT2	+ 58	2	0.512(b)	55	101	0.205	6.5	4.5	
	H	+ 75	1	0.666	58	112	0.266	7.5	5.5	
	CT9	75	2	0.630	56	104	0.252	7.5	5.5	
	CT7	+113	2	0.602(b)	59	116	0.241	10	6.5	
	F	+159	1	0.749	60	120	0.300	13	8.5	
	G	+200	1	0.859	64	137	0.344	15.5	10	
A517F	73B320	-148	(d)	0.648	56	104	0.259	17	6.0	-125
		-112		1.012	70	163	0.405	23.5	9.5	
		-103		1.258	78	203	0.503	25.5	11.5	
		- 93		1.528	86	246	0.611	28	13.8	
		- 83		1.825	94	294	0.730	31	16.0	
		- 72		2.190	102	347	0.876	34.5	18.3	
		- 56		2.780	116	448	1.112	40	22.9	
		- 39		3.492	130	563	1.397	48	27.5	

(a) On the upper shelf (with respect to transition temperature).
(b) Average of three tests.
(c) Estimated from PCI transition temperature.
(d) See Ref. (2) Figures 3 & 9; bend tests 1/2, 1 and 2-in. thick, 4-in. deep.

several of the data points from the A and M plates tested in and below the transition-temperature region, if plotted, would have been widely scattered to the left of the correlation curve.

Figure 30 is a plot of precrack Charpy impact (PCI) data. Note that except for the plate-M test, the scatter was somewhat reduced; only the valid K_{Ic} data were plotted. Figure 31 is the same plot as Figure 30 except that the abscissa has been expanded. The relationship

$$K_{Ic}^2/E = 18 \text{ (PCI)} \tag{11}$$

gives a conservative estimate of the static K_{Ic} value at any test temperature in or below the transition-temperature range.

Through-Thickness-Yielding Criterion

In practical application of the through-thickness yielding criterion, there is the tacit assumption that the nil-ductility transition (NDT) temperature of a given material will be lower than the lowest anticipates service temperature, and that with use of the Charpy V-notch (10-mil radius) upper-shelf-energy correlation, the start of the upper shelf will be at or below the lowest anticipated service temperature (as in the case of plate M of Figure 28). In the U.S. Steel researches where through-thickness-yielding was proposed as a criterion of acceptable toughness for critical applications, the A517-F steel under consideration developed Charpy V-notch (10-mil radius) impact shelf-energy levels at room-temperature or lower. Four out of five of the U.S. Steel studies reviewed in connection with this study dealt with a single heat of A517-F, viz., heat 73A377 (see the Tables of Appendix B). Using the through-thickness-yielding criterion proposed by the U.S. Steel investigators, heat 73A377 with yield strength ranging from 110 to 121 ksi would have to develop 50 to 54 ft-lb of Charpy shelf energy at the lowest anticipated service temperature to meet the through-the-thickness yielding criterion for 2-in. thick plate. The reported CVN impact self values at 80°F ranged from 47 to 62 ft-lb (see Tables of Appendix B). From Figure 2 it will be seen that the CVN upper shelf for this heat of A517-F was below 0°F.

TABLE 13

CHARPY ENERGY REQUIREMENTS FOR THROUGH-THICKNESS YIELDING

Steel Type	Plate No.	Yield Strength (ksi)	CVN Upper Shelf Temp. (°F)	CVN Upper Shelf Energy (ft-lb)	CVN Energy Required[a] (ft-lb)
A514F	M(ZU)	119	0	65	59
	L(ZV)	109	40	77	54
A517F	A(ZW)	100	200	40	50
A514H	R(ZX)	109	200	56	54
	Z(ZT)	115	200	55	58
A517H	AL(ZY)	100	200	42	50
	Q(ZZ)	109	200	16	54

(a) CVN $\geq$ FTY (B + 0 .25)/5 and for 2-1/4-in. plate CVN $\geq$ 0.50 FTY

Of the seven A514/517 steels investigated in this study, five of the seven had CVN upper shelves starting at a temperature of 200°F or higher. From Table 13 it will be seen that at the temperature corresponding to the CVN-impact-energy upper shelf, only three of the seven A514/517 steels investigated in this study (plates L, M and R) developed the required energy levels to give through-thickness yielding in 2-1/4-in. plate based on the standard Charpy V-notch (10-mil radius) test. However, only in U.S. Steel A514-F plate M was the upper shelf at or below 0°F. Plate L was borderline with the shelf starting at about 40°F; based on a shelf energy of 77 ft-lb, plate L more than met the through-thickness-yielding criterion.

The situation for plate L described above points up a limitation on use of the upper-shelf correlation as a basis for the through-thickness yielding criterion. If the Charpy upper shelf does not occur at or below the lowest anticipated service temperature, the through-thickness-yielding criterion can be misleading. For example, consider the case of a 2-1/4-in.-thick U.S. Steel

A514-F plate (heat 72A033-033429). For a 2-1/4-in.-thick plate at 115 ksi yield strength, the through-thickness-yielding criterion requires 57.5 ft-lb at the lowest anticipated service temperature. The following are the Charpy V-notch impact test results obtained from the plate*:

Test Temp. (°F)	CVN Energy (ft-lb)
+120	81
+ 72	84
+ 20	37 (38.8, 26.9, 46.9)

Thus, if the Charpy V-notch impact tests had been taken only at room temperature, the steel would have been indicated to more than meet the required toughness for through-thickness yielding, but at 20°F the steel was undergoing the ductile-to-brittle transition and was in fact deficient in toughness.

A through-thickness-yielding criterion based on transition-temperature-range correlations was obtained by combining the Hahn and Rosenfield expression

$$(K/FTY)^2/B = 1$$

and the CVN-K_{Ic} correlation

$$K_{Ic}{}^2/E = 2\ (CVN)^{3/2}$$

This provided the following relationship:

$$FTY^2 = 2(CVN)^{1.5}\ E/B \qquad (12)$$

Of the seven steels in this investigation, only U.S. Steel plates L and M met this criterion at 0°F. Also the two heats of A517-F used in the U.S. Steel researches met the criterion at 0°F. However, U.S. Steel A514-H plate R, Lukens A517-F plate A, and Lukens A517-H plates AL, Q and Z all failed to meet the criterion even for 1-in. thickness.

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*Charles Kendrick, private communication.

Charpy data* from several additional plates of ASTM A514/517 steel were examined for compliance with the proposed criterion. The plates were 1-1/2, 2, 2-1/4 and 2-1/2-in. thick. The 1-1/2-in.-thick plates came from four U.S. Steel heats of A517-F; data were available from nine slabs. The 2-in.-thick plates came from two Lukens heats of A517-H; data were available from four slabs (plates E, F, G and H). The 2-1/4-in.-thick plate came from a Lukens heat of A517-F (plate A). The 2-1/2-in.-thick plates came from a Lukens heat of A517-F (plate B), a Lukens heat of A517-H (plate C) and a U.S. Steel heat of A517-F (plate D). Figure 32 is a plot of these data superimposed on the curves relating yield-strength and CVN impact for through-thickness yielding. From Figure 32, it will be seen that eleven of the A514/517 plates would not meet the through-thickness yielding criterion for even 1-in. thickness. Eight of the nine U.S. Steel 1-1/2-in.-thick A517-F plates complied with the criterion; six of the 1-1/2-in. plates met the toughness requirement for 2-in. plate.

A comparison of criteria based on the upper-shelf and transition-temperature-range correlations is shown in Figure 33. Only the data for steels which developed upper-shelf energy at or below 0°F are plotted. Note that all the plates which developed upper-shelf energy at or below 0°F met the through-thickness-yielding criterion based on the upper-shelf correlation. The dash curves in Figure 33 are from Figure 32; thus, the dash curves represent the through-thickness-yielding criterion based on the U.S. Steel K_{Ic}-CVN transition-temperature-range correlation. The superposition shows that the criterion based on the K_{Ic}-CVN upper-shelf correlation is less stringent and, therefore, perhaps more practical, providing the steel companies can provide plate with the CVN upper shelf at or below temperate-zone service temperatures.

Combining the Hahn and Rosenfield expression

$$(K/FTY)^2/B = 1$$

and the PCI-K_{Ic} correlation

$$K_{Ic}^2/E = 18\ (PCI)$$

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*Charles Kendrick, private communication.

provided the following relationship for a through-thickness-yielding criterion based on the precrack Charpy impact transition-temperature-region test results:

$$PCI = FTY^2 \cdot B/18E \tag{13}$$

Of the seven steels in this investigation, only U.S. Steel plate M came close to meeting this criterion at 0°F. U.S. Steel heat 73B320 and U.S. Steel plate L both failed to meet the criterion in their respective thicknesses. Figure 34 is a plot of these data superimposed on the curves relating yield strength and PCI (ft-lb) for through-thickness yielding; the same data are plotted as in Figure 32. Note that all of the 1-1/2-in.-thick U.S. Steel plates met the criterion except one. None of the Lukens plates met the through-thickness yielding criterion for even 1-in. thickness; U.S. Steel plates R and L also failed to meet even the 1-in.-thickness criterion.

Another approach providing a criterion for through-thickness yielding is based on the plane-stress plastic-zone expression

$$r_p = (K/FTY)^2/2\pi$$

If this expression is equated to the plate thickness (i.e., a plastic zone equal to the plate thickness) and if E(W/A) as determined from the precrack Charpy impact test is substituted for K^2, assuming a nominal crack depth of 0.035 inch

$$W = 2.31 \times 10^{-8}\, B \cdot FTY^2 \tag{14}$$

where W/12 is the precrack Charpy energy value in units of ft-lb. When this criterion was used as a basis for determining the precrack Charpy energy for through-thickness yielding, the values were for all practical purposes the same as those calculated based on equation (13). The following tabulation shows the similarity of the two criteria:

	PRECRACK CHARPY CRITERIA (FT-LB) FOR THROUGH-THICKNESS YIELDING				CVN (ft-lb) Measured at 0°F	
	$FTY^2 \cdot B/18E$		$FTY^2 \cdot 2\pi B/E$			
Plate	1 in.	2 in.	1 in.	2 in.	FTY	PCI
M	26	52	27	55	119	52
L	24	46	25	48	112	23

CONCLUSIONS

The seven ASTM A514/517 steels investigated showed marked heat-to-heat variations in fracture behavior and, with one exception, markedly poorer fracture behavior than the two heats of ASTM A517-F used in the U.S. Steel researches. Heat-to-heat variations in the extent of strain-rate embrittlement precluded a 1:1 correlation between precrack Charpy impact and static compact-tension transition behavior. The empirical K_{Ic}-CVN relationship reported by U.S. Steel based on upper-shelf Charpy energy values could not be used in five of the seven steels tested because the Charpy upper shelf occurred well above bridge-service temperatures. The through-thickness-yielding criterion proposed by U.S. Steel investigators utilizes the upper-shelf correlation; therefore, this criterion is only applicable for steels developing full shelf energy in the Charpy test at or below the lowest anticipated service temperature. The through-thickness-yielding concept was evaluated using K_{Ic}-CVN transition-temperature correlations; useful criteria were established based on both the standard Charpy V-notch and the precrack Charpy impact tests.

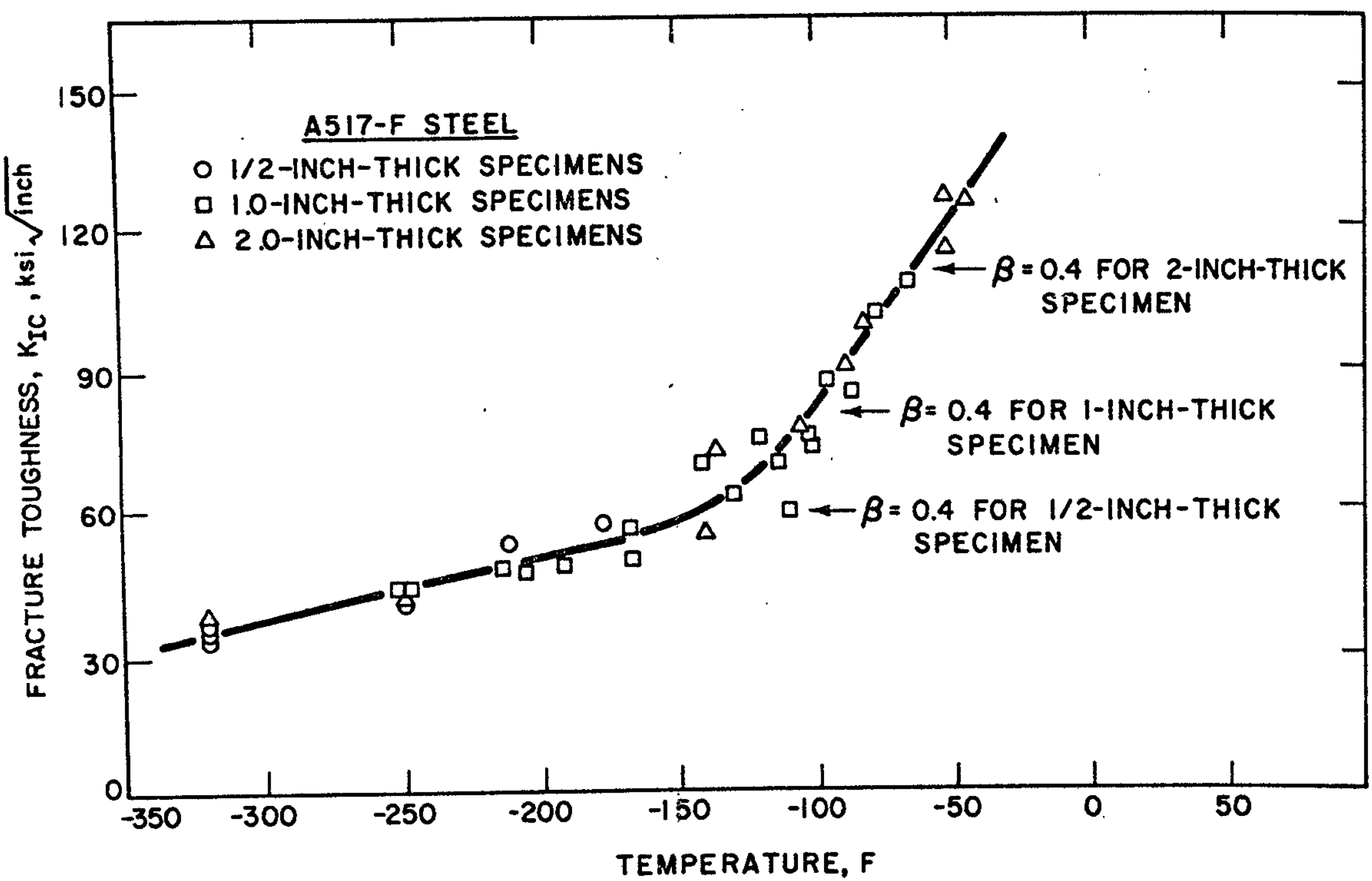


Figure 1. Plane-Strain Fracture-Toughness Behavior of A517-F Steel (Heat 73B320) as a Function of Temperature (Ref. 2).

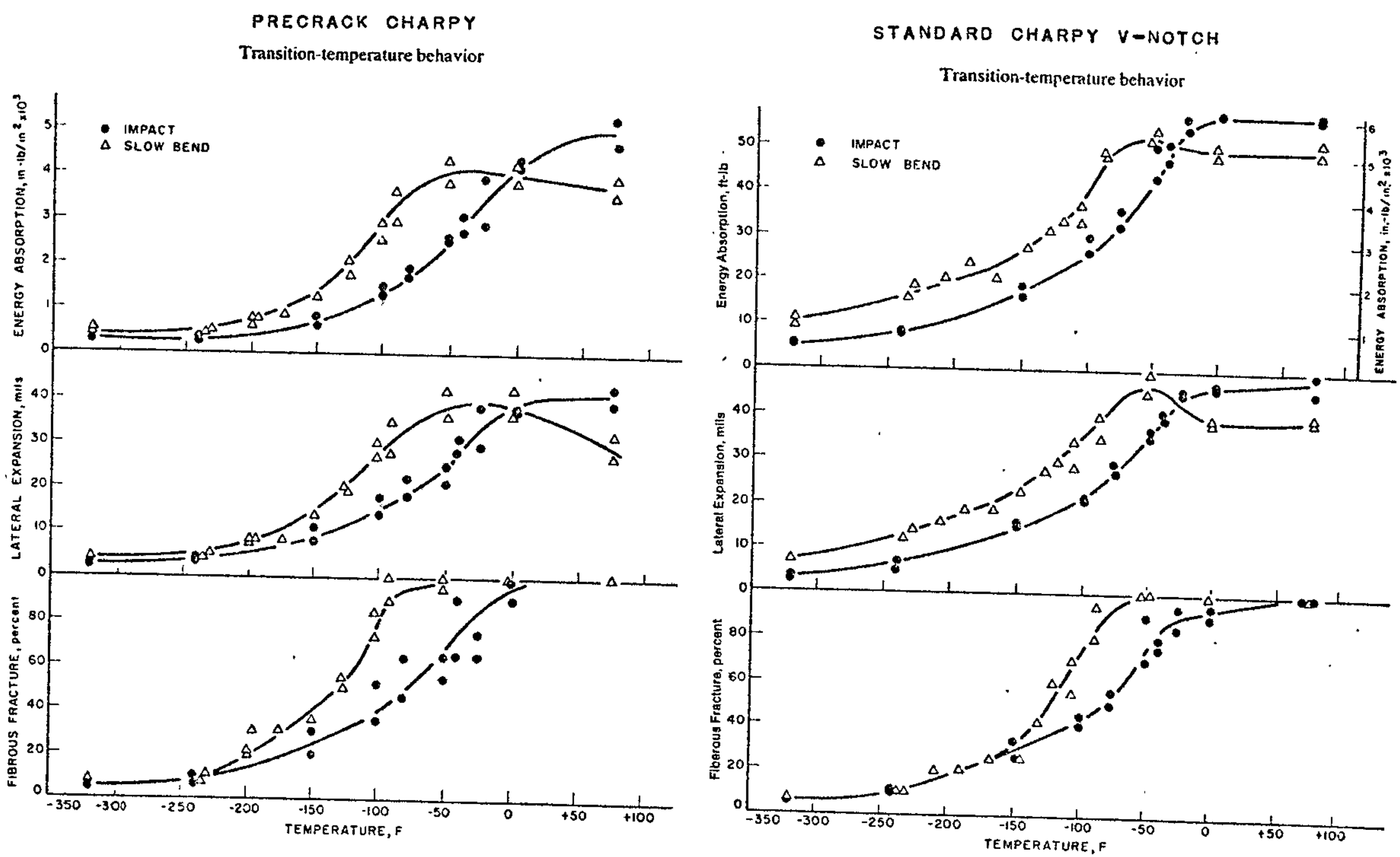


Figure 2. Energy Absorption, Lateral Expansion and Fibrous Fracture for Precrack Charpy Impact (PCI) and Standard Charpy V-Notch (CVN) Impact of A517-F Heat 73B320 (Ref. 2).

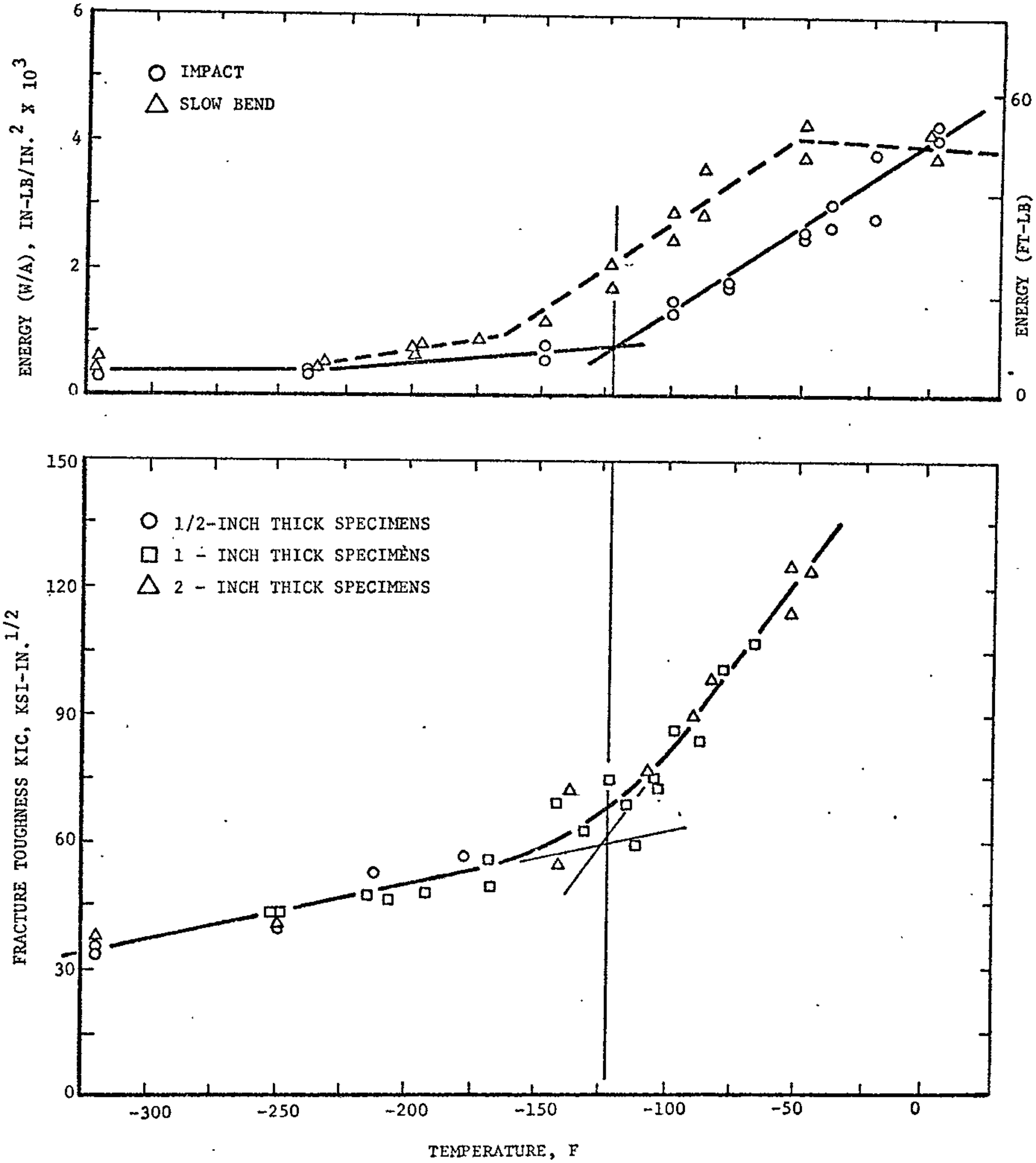


Figure 3. Correlation of Transition Temperatures in K_{Ic} and PCI Tests of A517-F Heat 73B320.

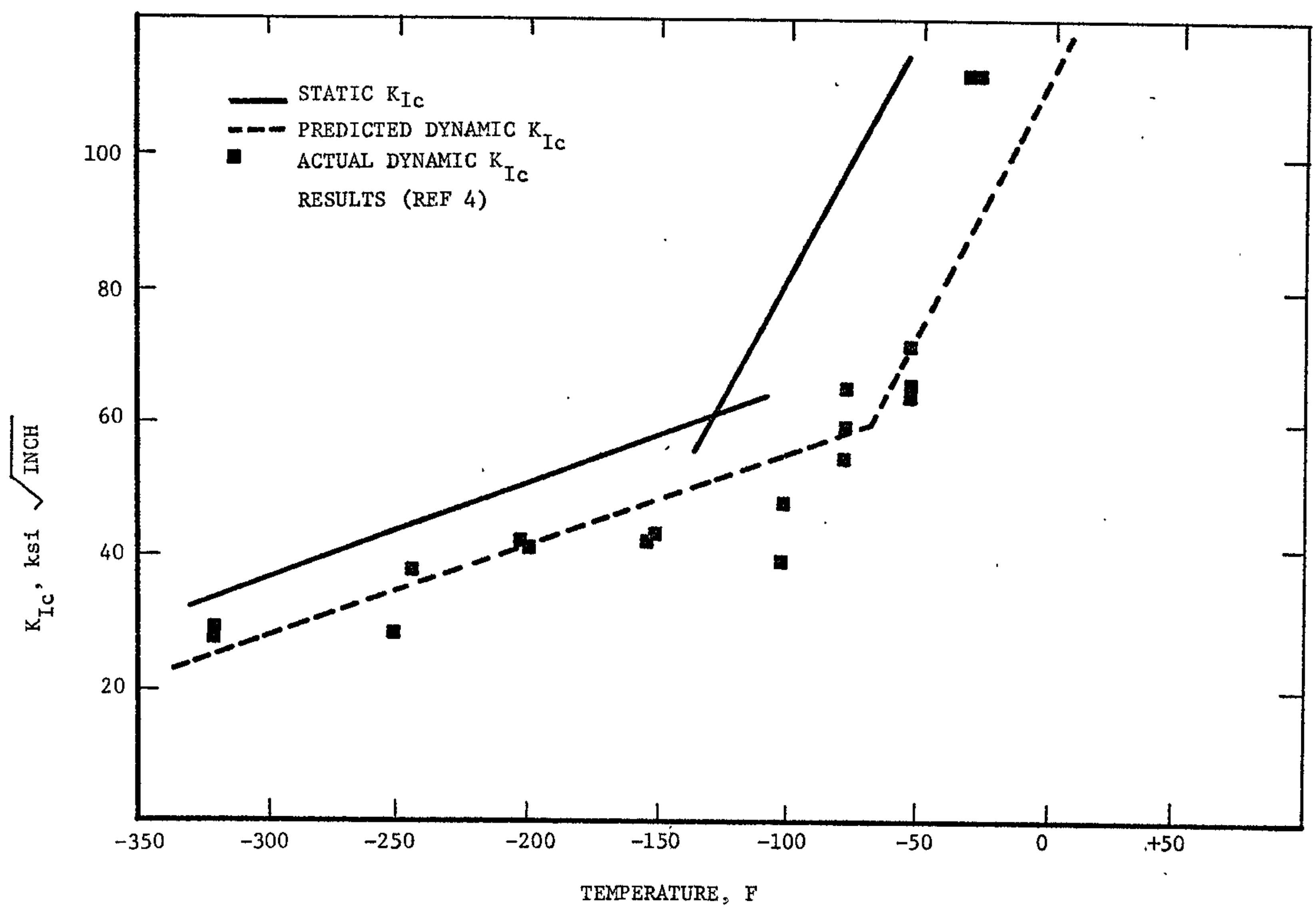


Figure 4. Predicted Dynamic K_{Ic} Behavior of A517-F Heat 73A377 (Ref. 2).

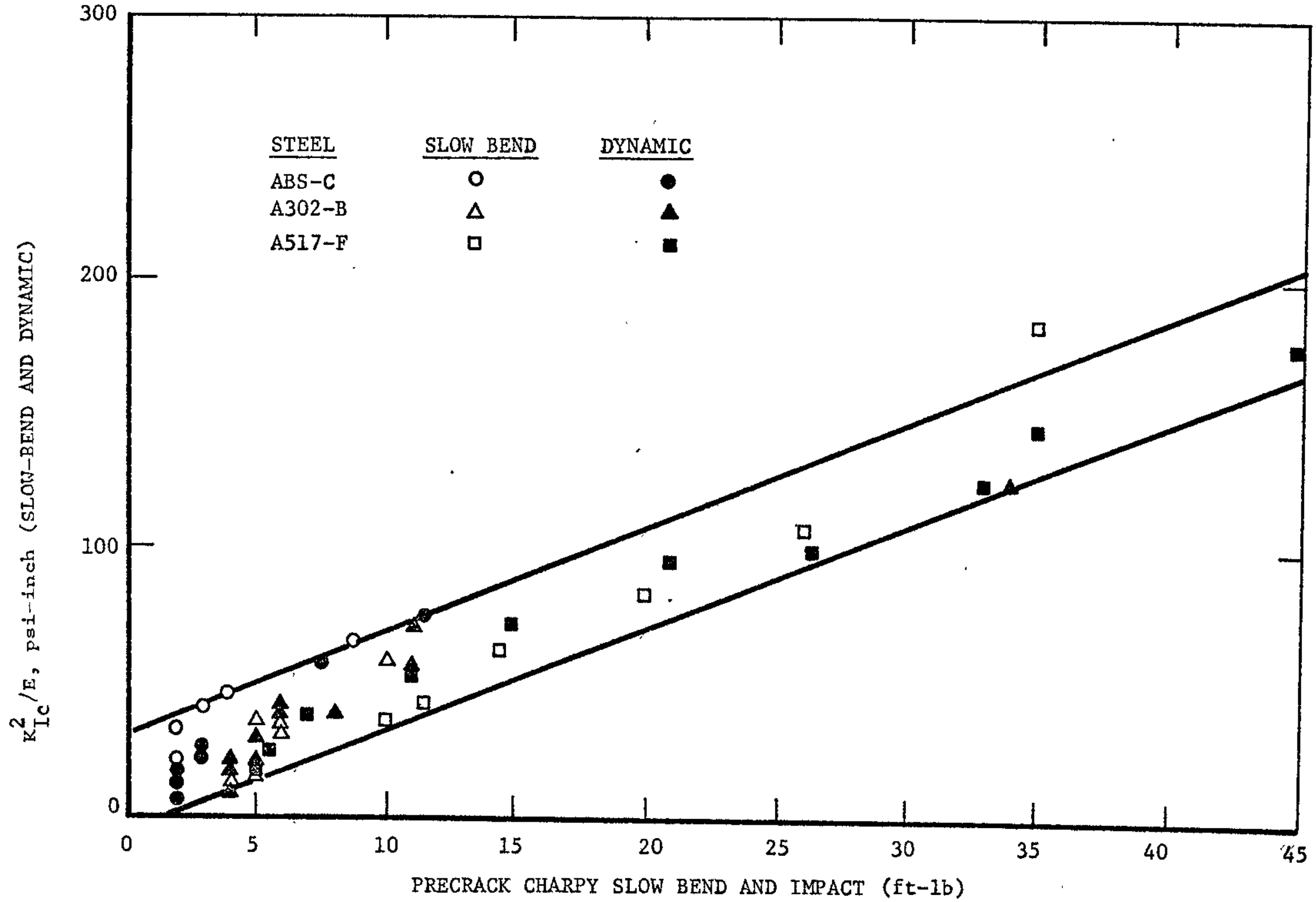


Figure 5. Correlation Between K_{Ic} and Charpy Test Results for Slow-Bend and Dynamic Loading (Ref. 4)

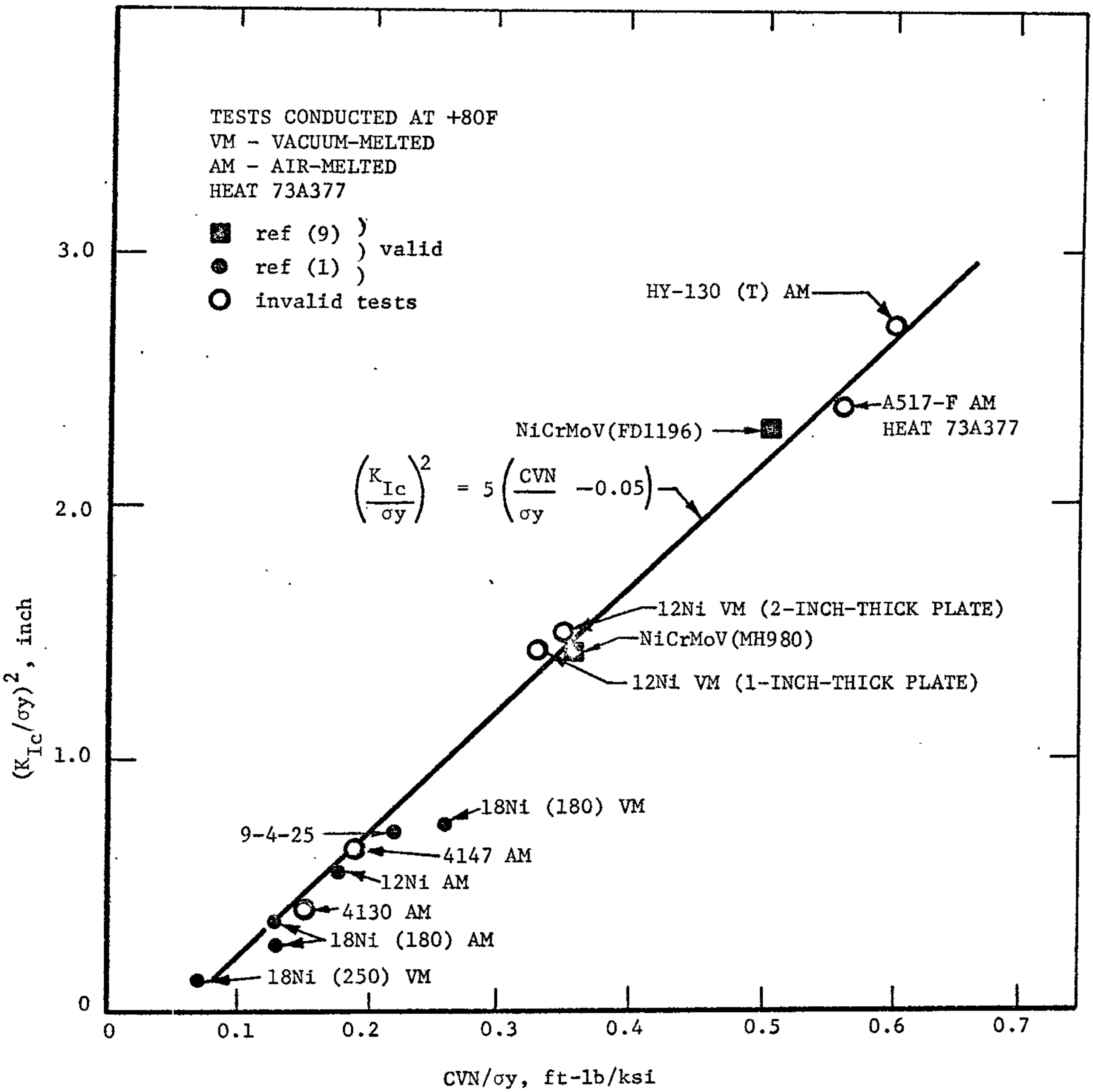


Figure 6. Relation Between Plane-Strain Stress-Intensity Factor, K_{Ic}, and Charpy V-Notch, CVN, Energy Absorption (Ref. 4).

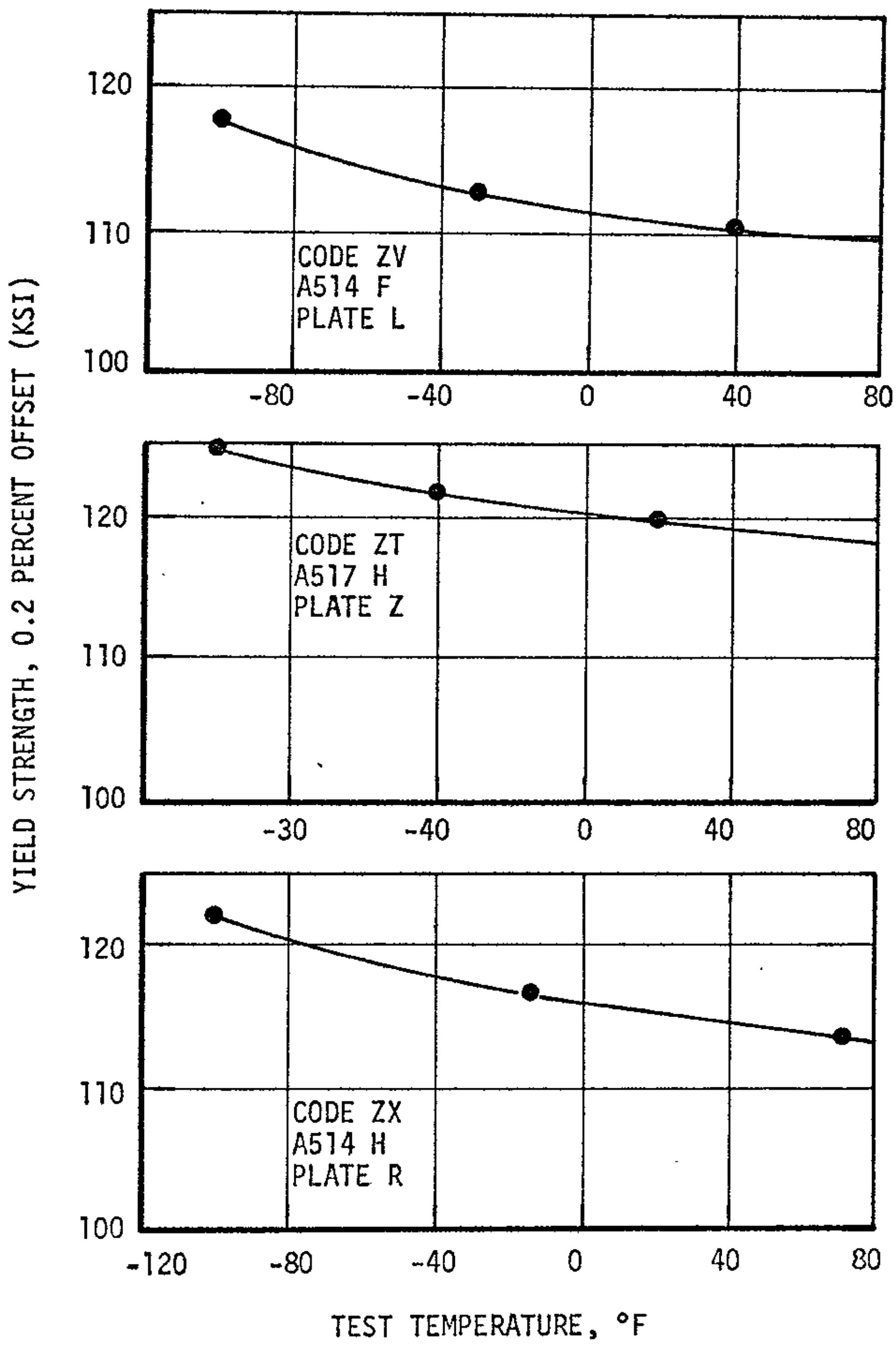


Figure 7. Yield Strength as a Function of Test Temperature in Plates L(ZV), R(ZX) AND Z(ZT).

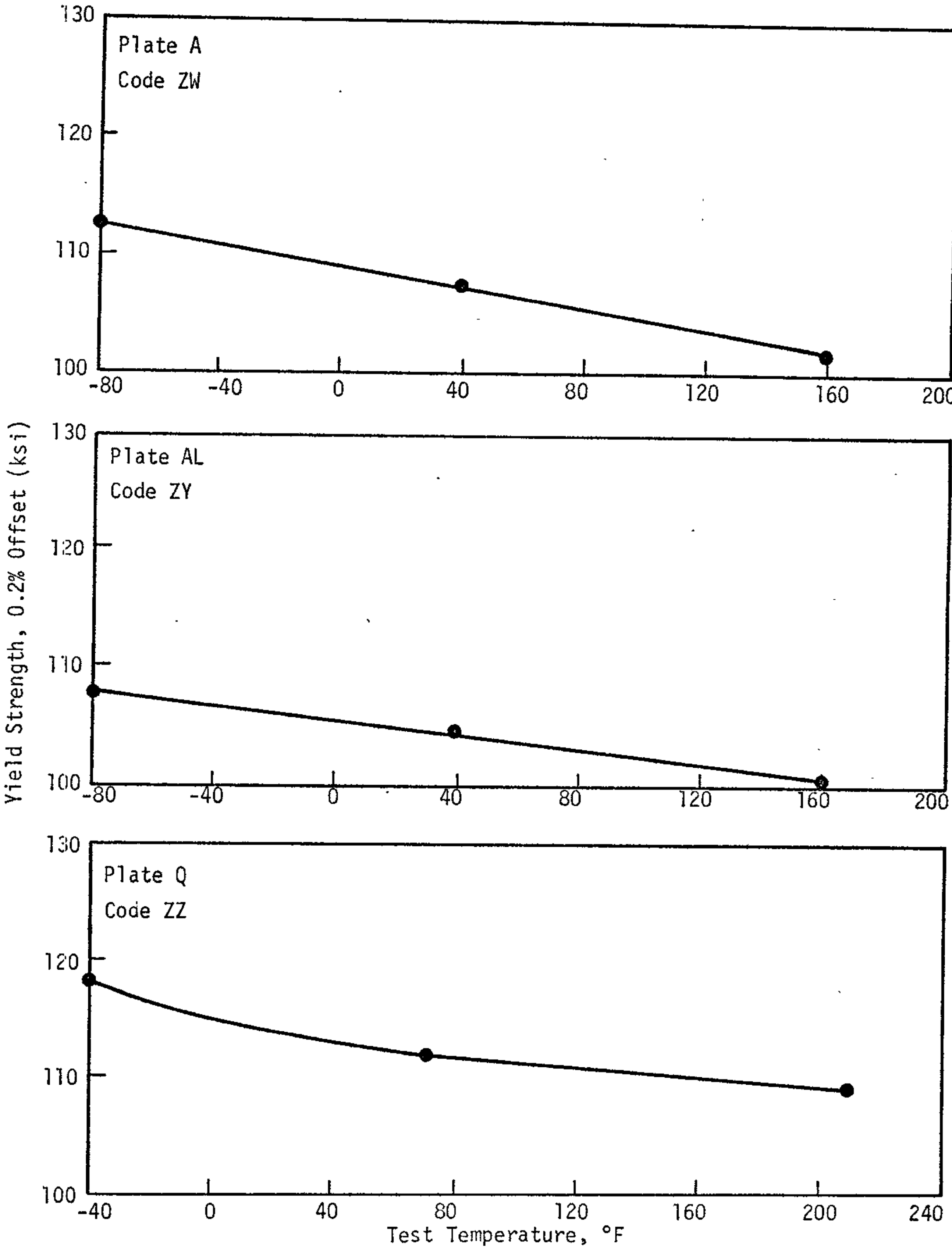


Figure 8. Yield Strength as a Function of Test Temperature in Plates A(ZW), AL(ZY), and Q(ZZ)

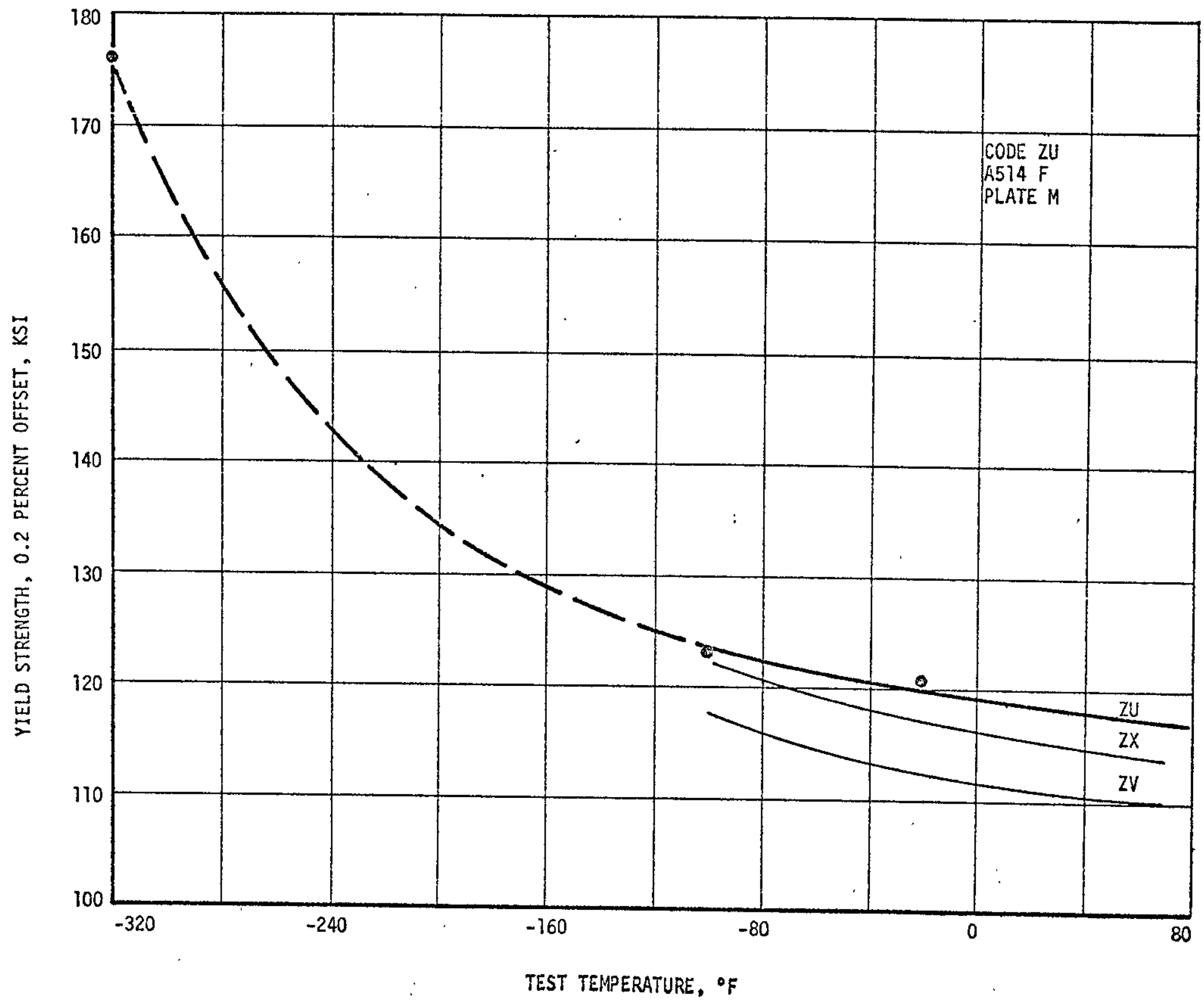
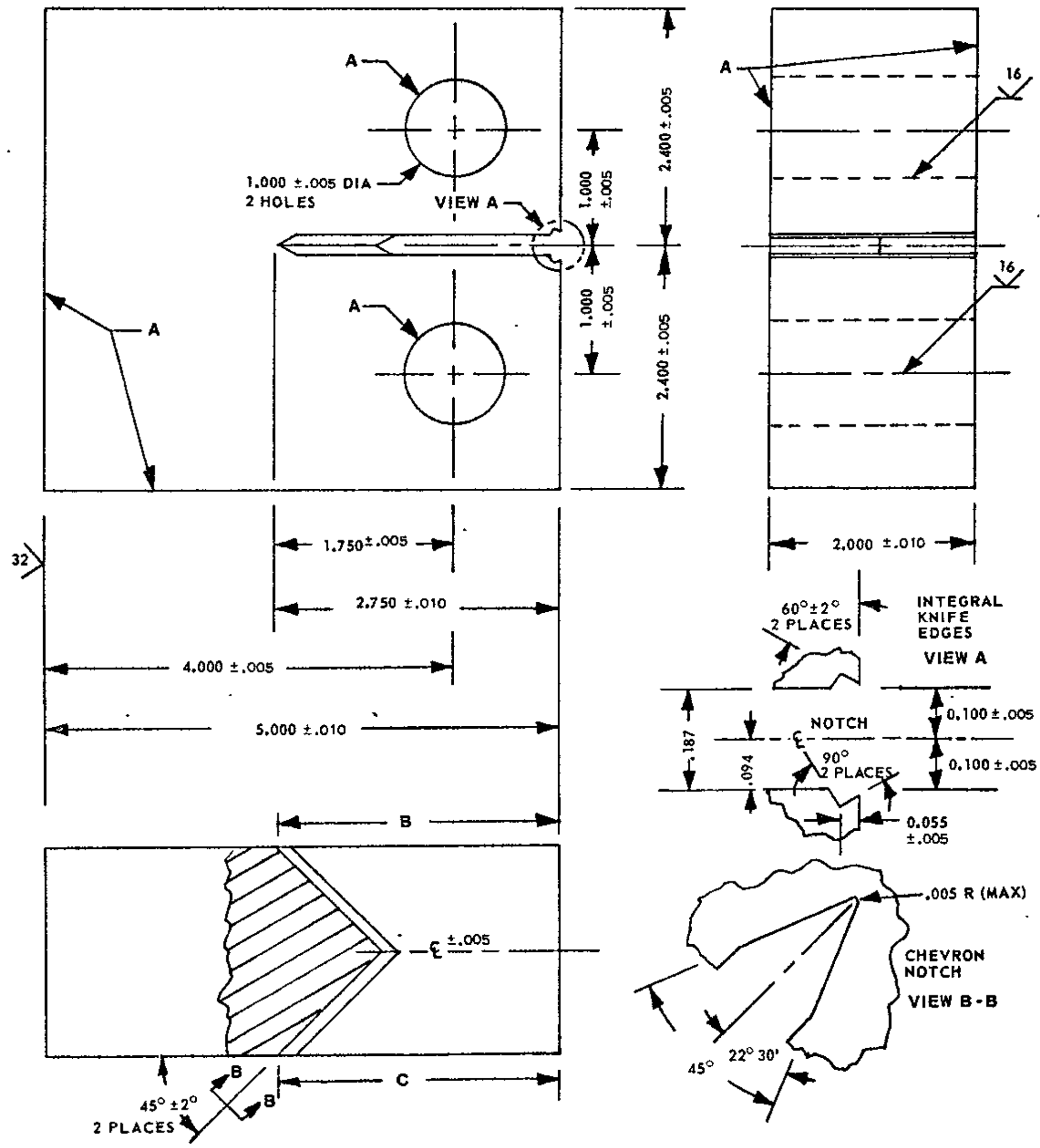


Figure 9. Yield Strength as a Function of Test Temperature in Plate M(ZU).



Note 1 – Dimensions are in inches.

Note 2 – A surfaces shall be perpendicular and parallel as applicable to within 0.008 TIR.

Note 3 – The points of intersection of the crack starter tips with the two specimen faces shall be equally distant from either pin hole center to within 0.020.

Note 4 – Each of the two parallel notch surfaces must lie in one plane to within 0.020 and must be perpendicular or parallel as applicable to the specimen faces to within 0.020.

Note 5 – B = C to within 0.020

Figure 10. Two-Inch-Thick Compact-Tension Specimen Dimensions and Tolerances.

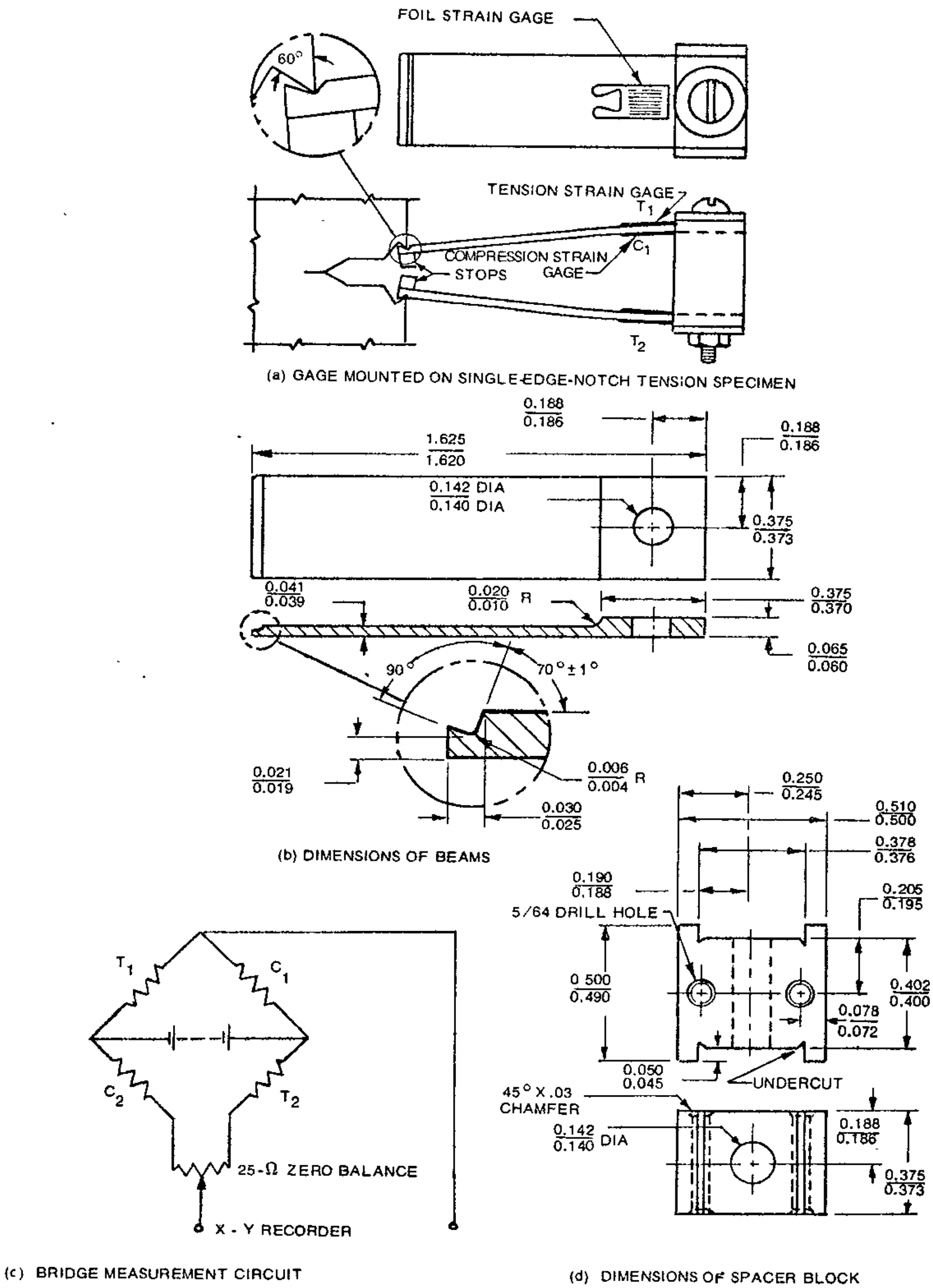


Figure 11. Double-Cantilever Displacement Gage
(all dimensions are in inches except where noted)

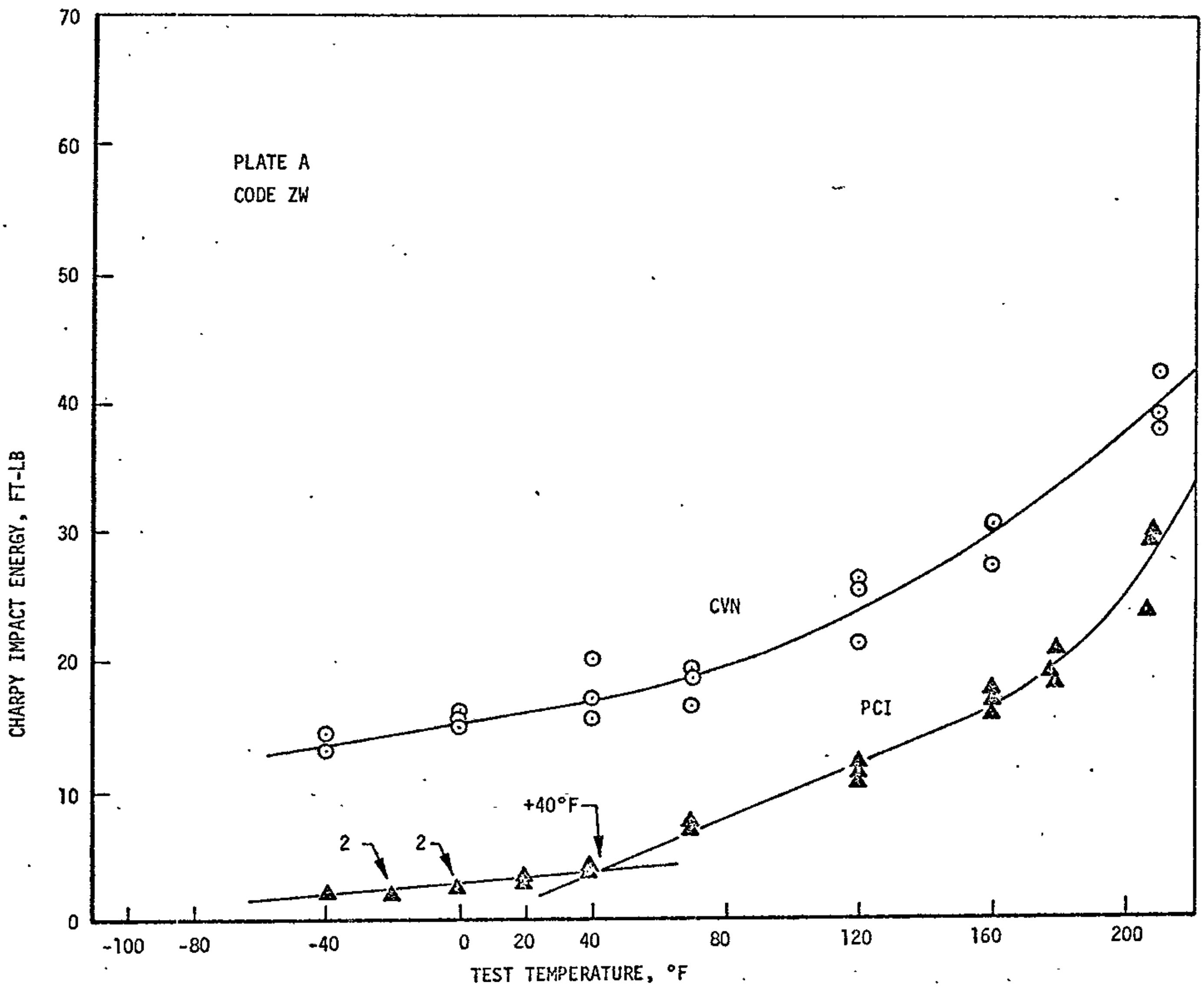


Figure 12. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate A(ZW).

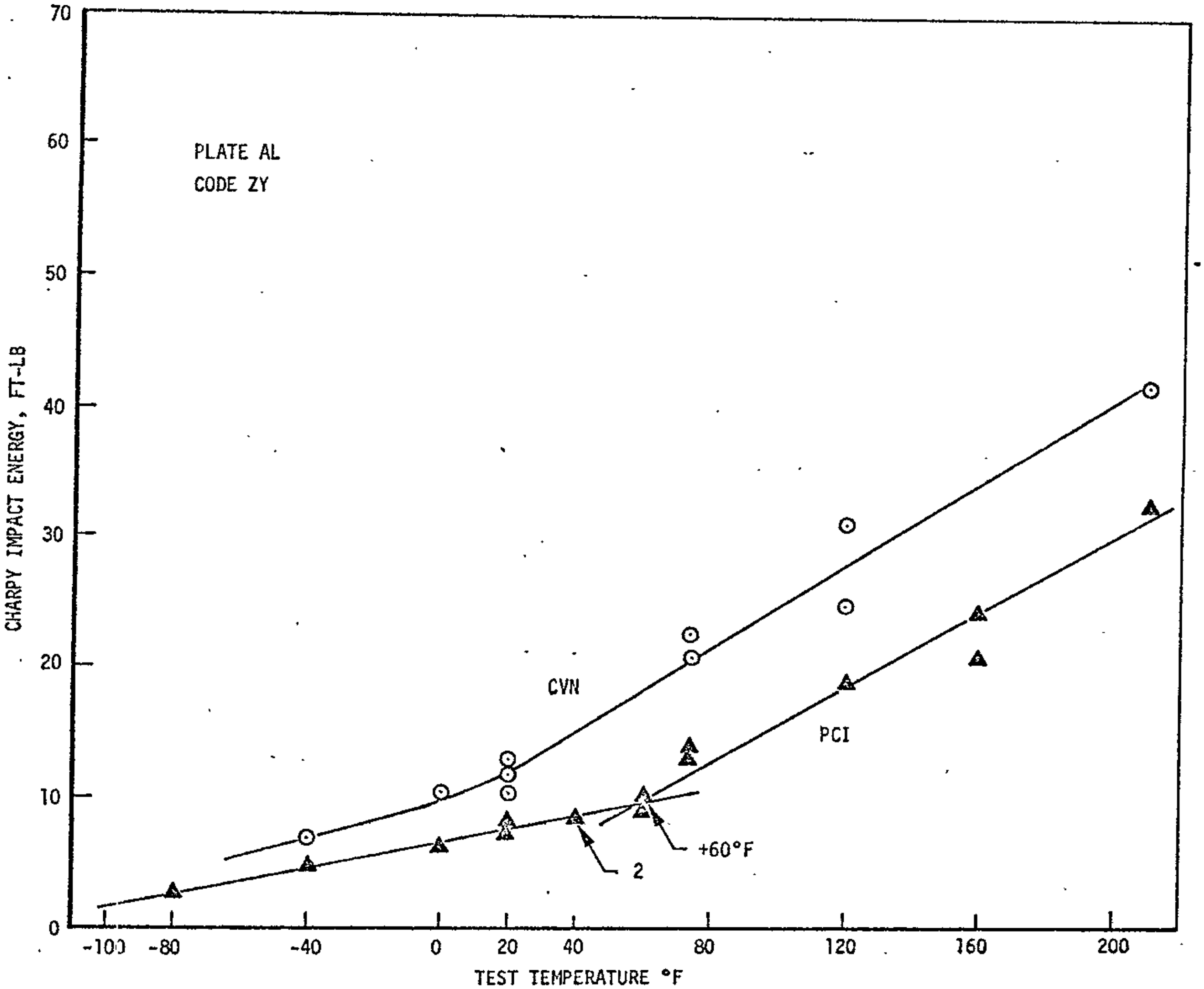


Figure 13. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate AL(ZY).

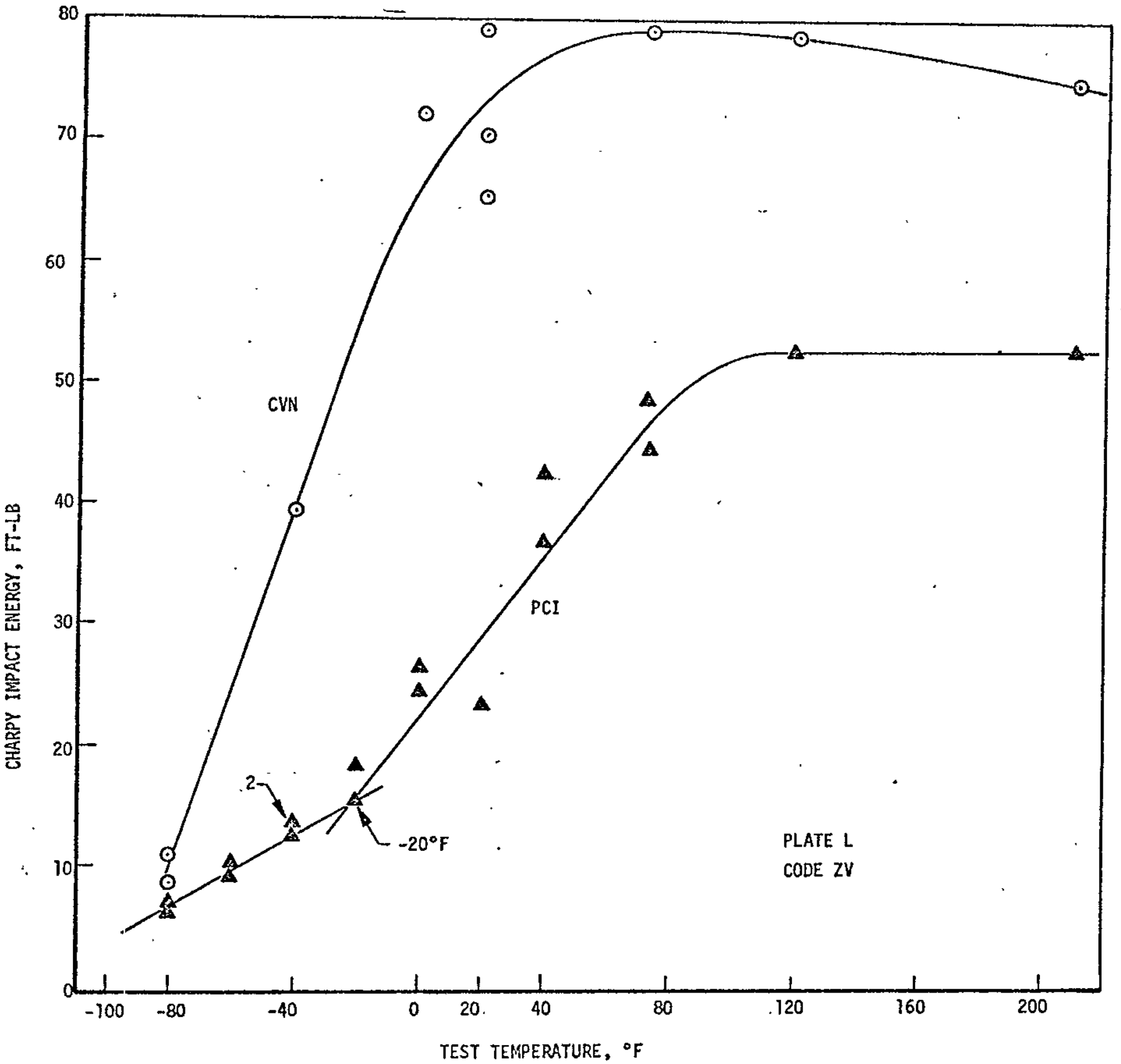


Figure 14. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate L(ZV).

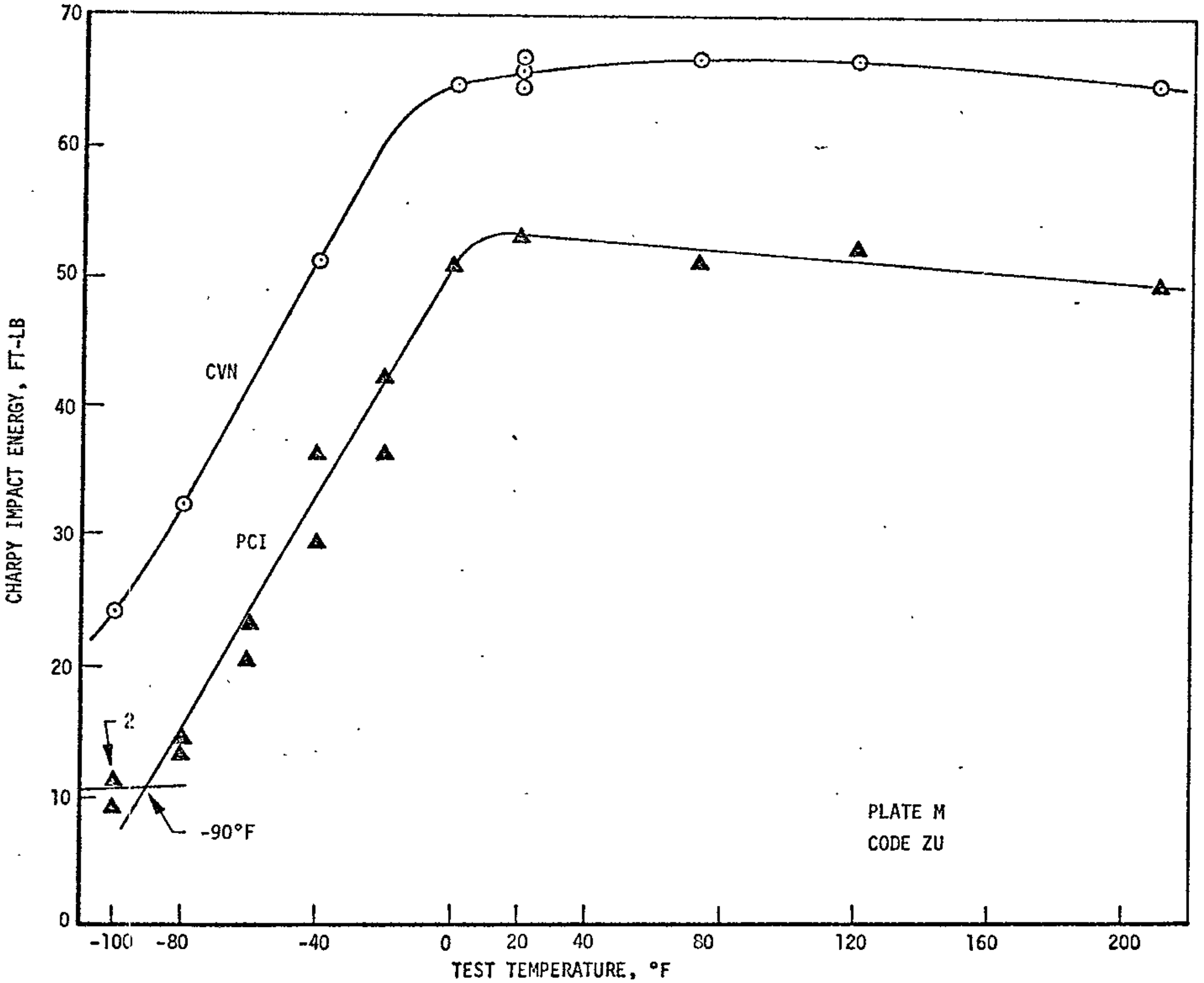


Figure 15. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate M(ZU).

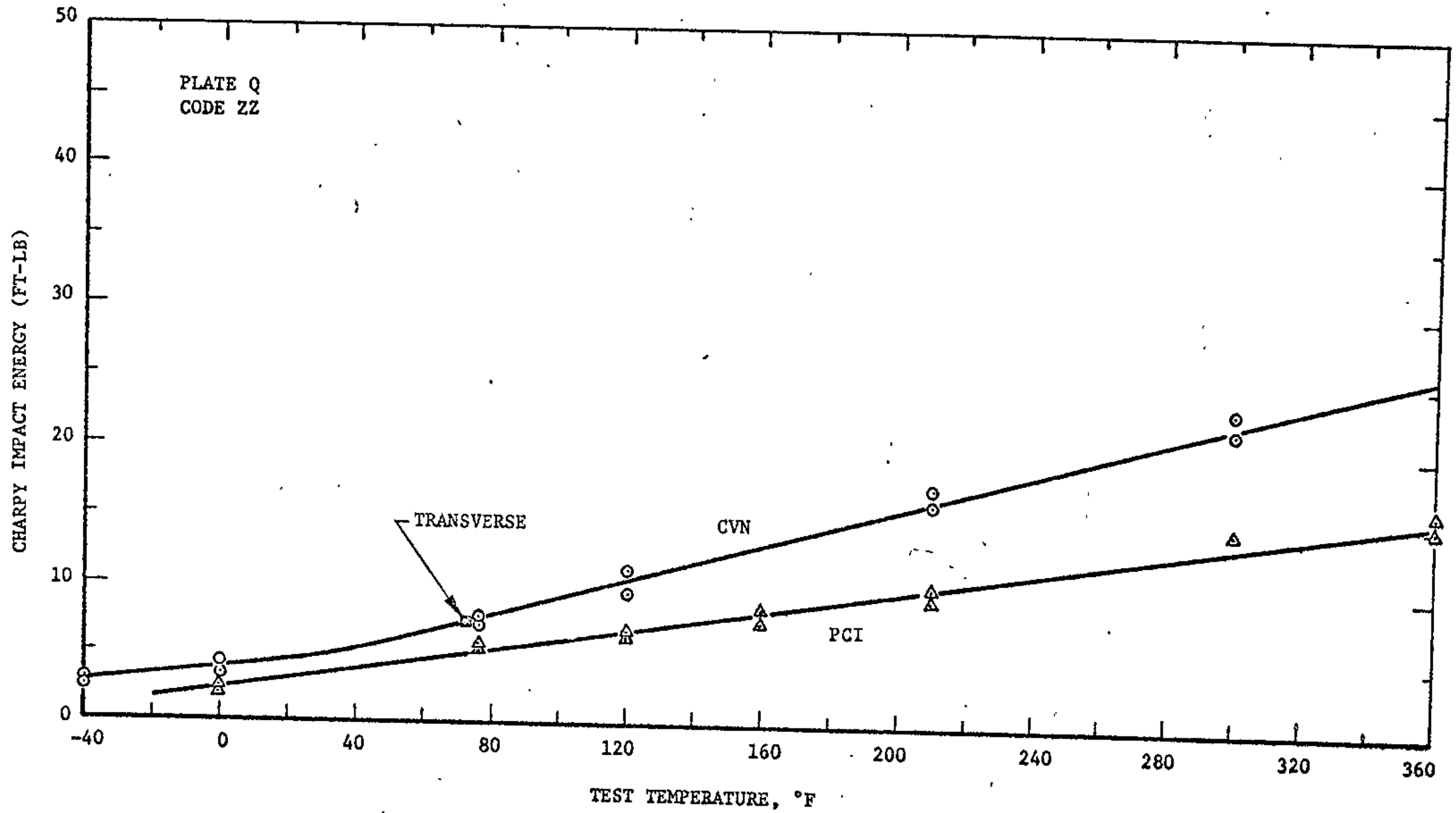


Figure 16. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate Q(ZZ).

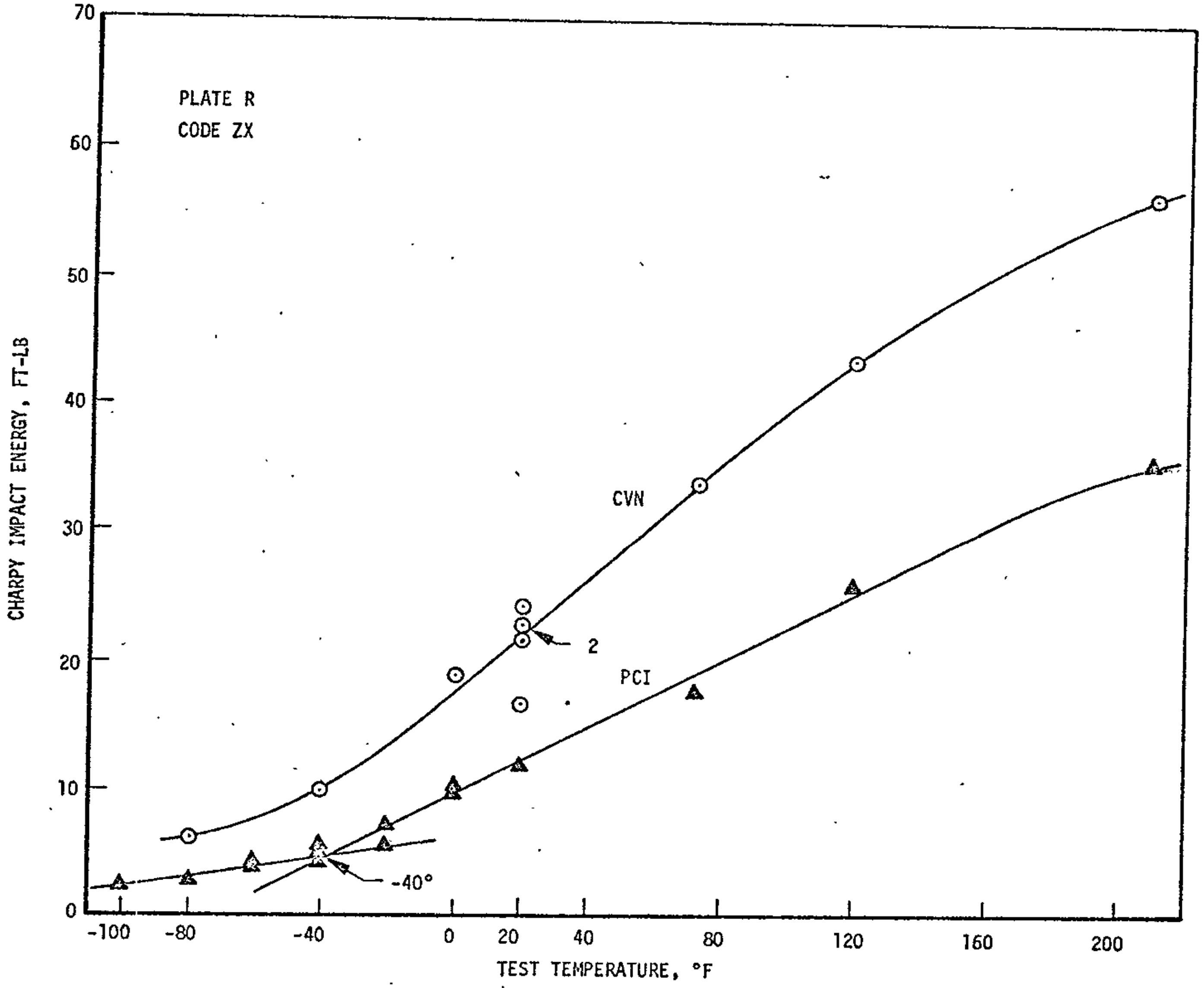


Figure 17. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate R(ZX).

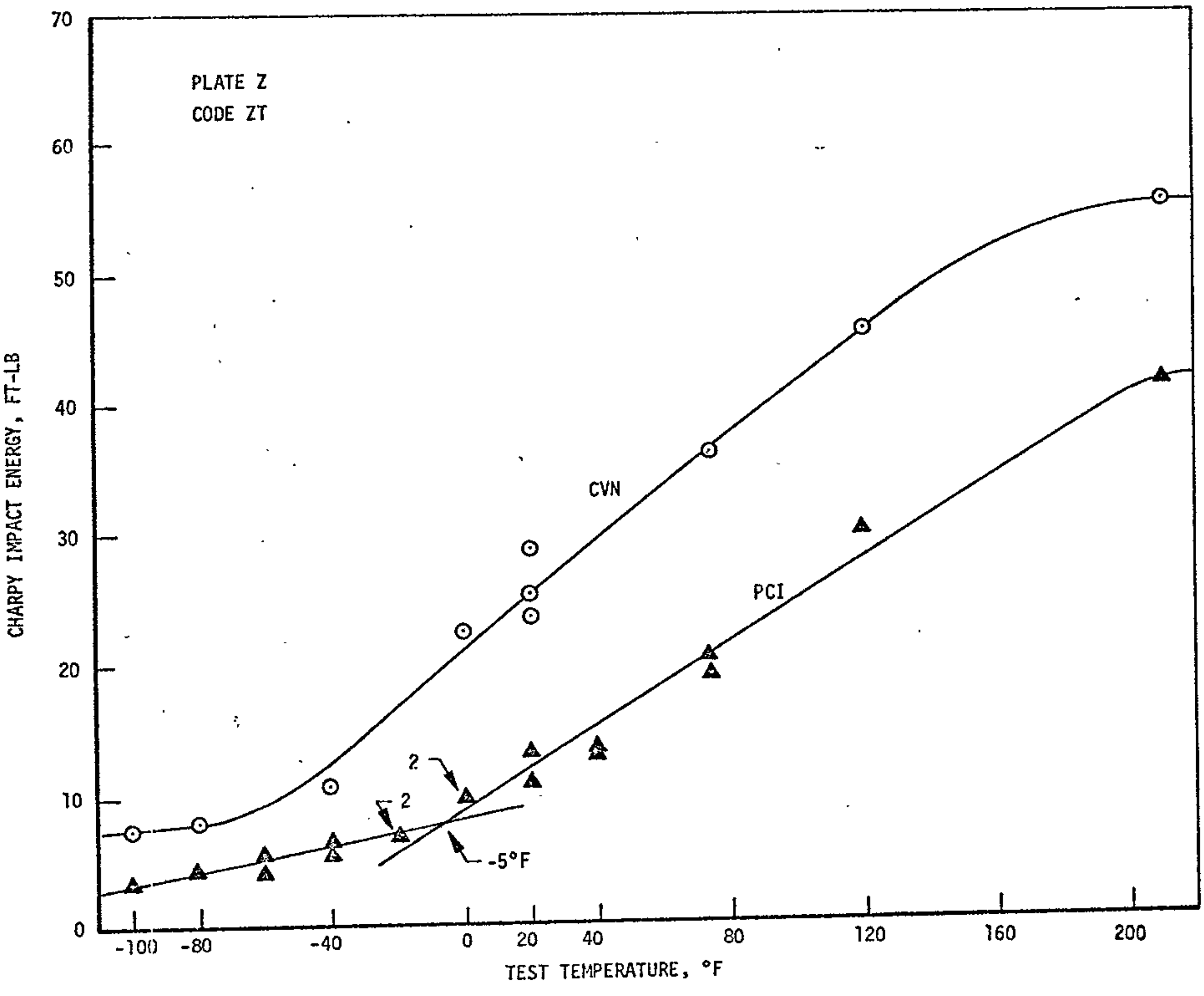


Figure 18. Standard (CVN) and Precrack Charpy Impact (PCI) Transition Curves for Plate Z(ZT).

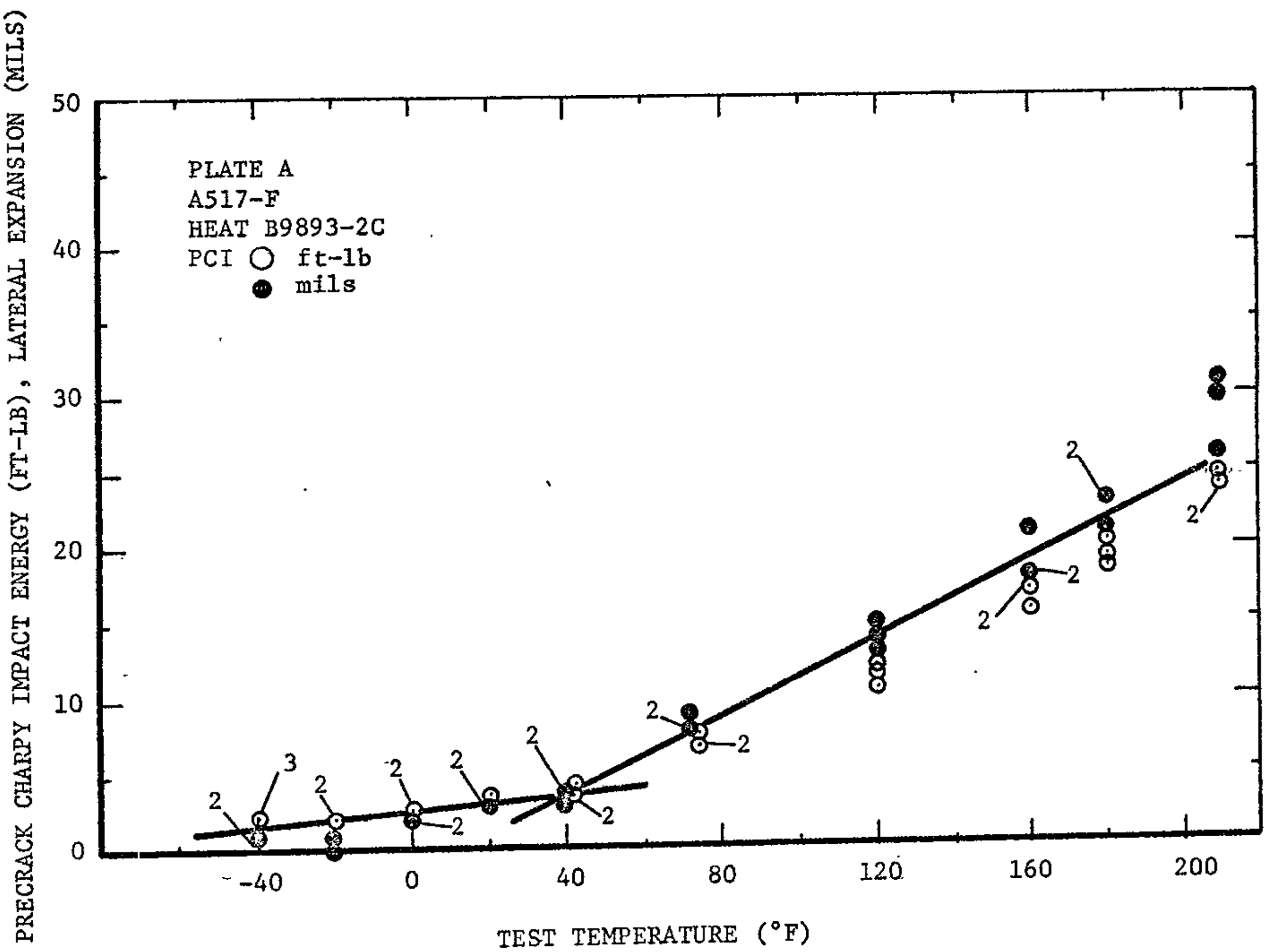


Figure 19. Energy Absorption and Lateral Expansion Precrack Charpy Impact (PCI) Transition Curves for Plate A(ZW).

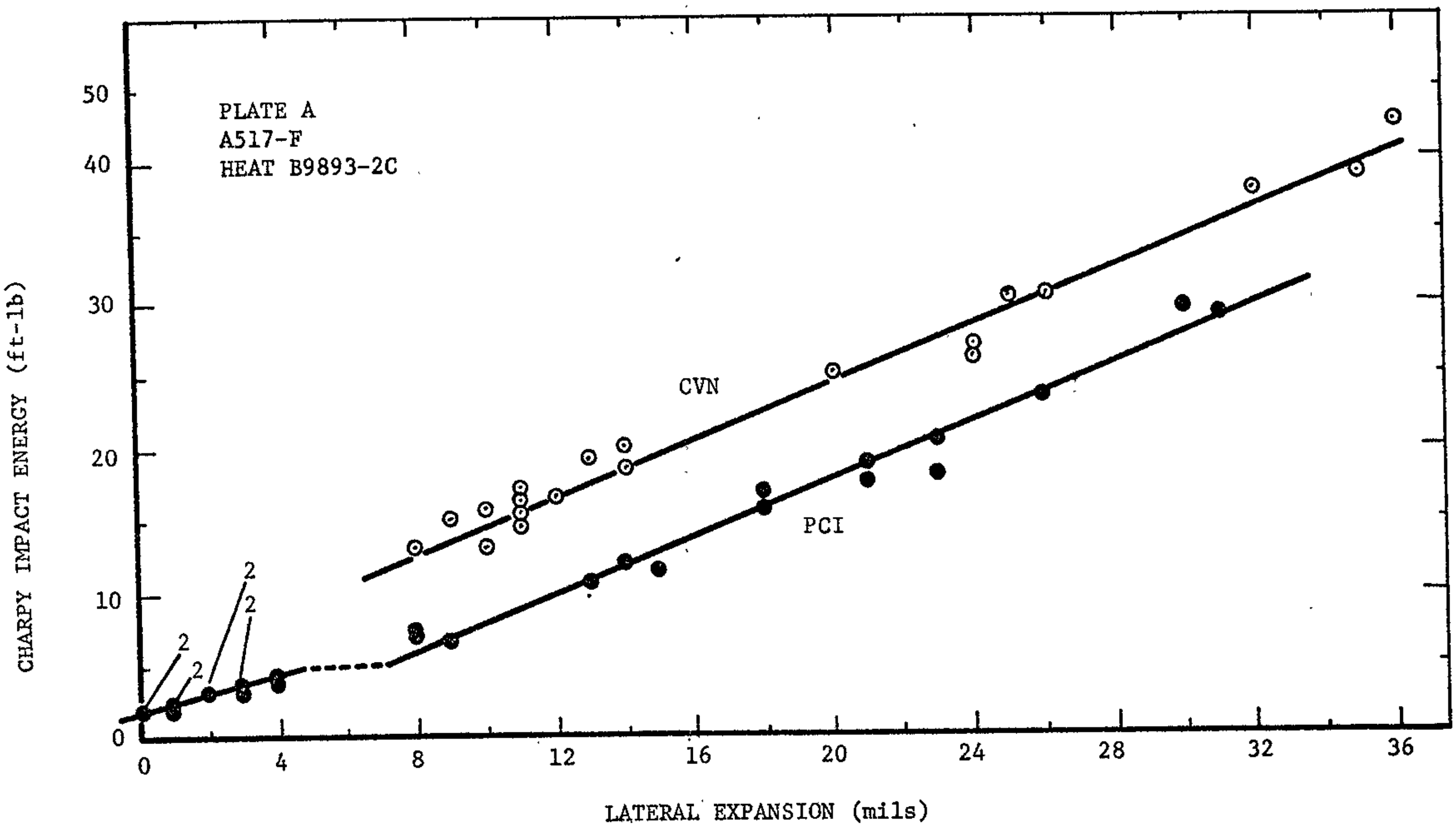


Figure 20. Relationship Between Lateral Expansion and Charpy Impact Energy (CVN and PCI) for Plate A(ZW).

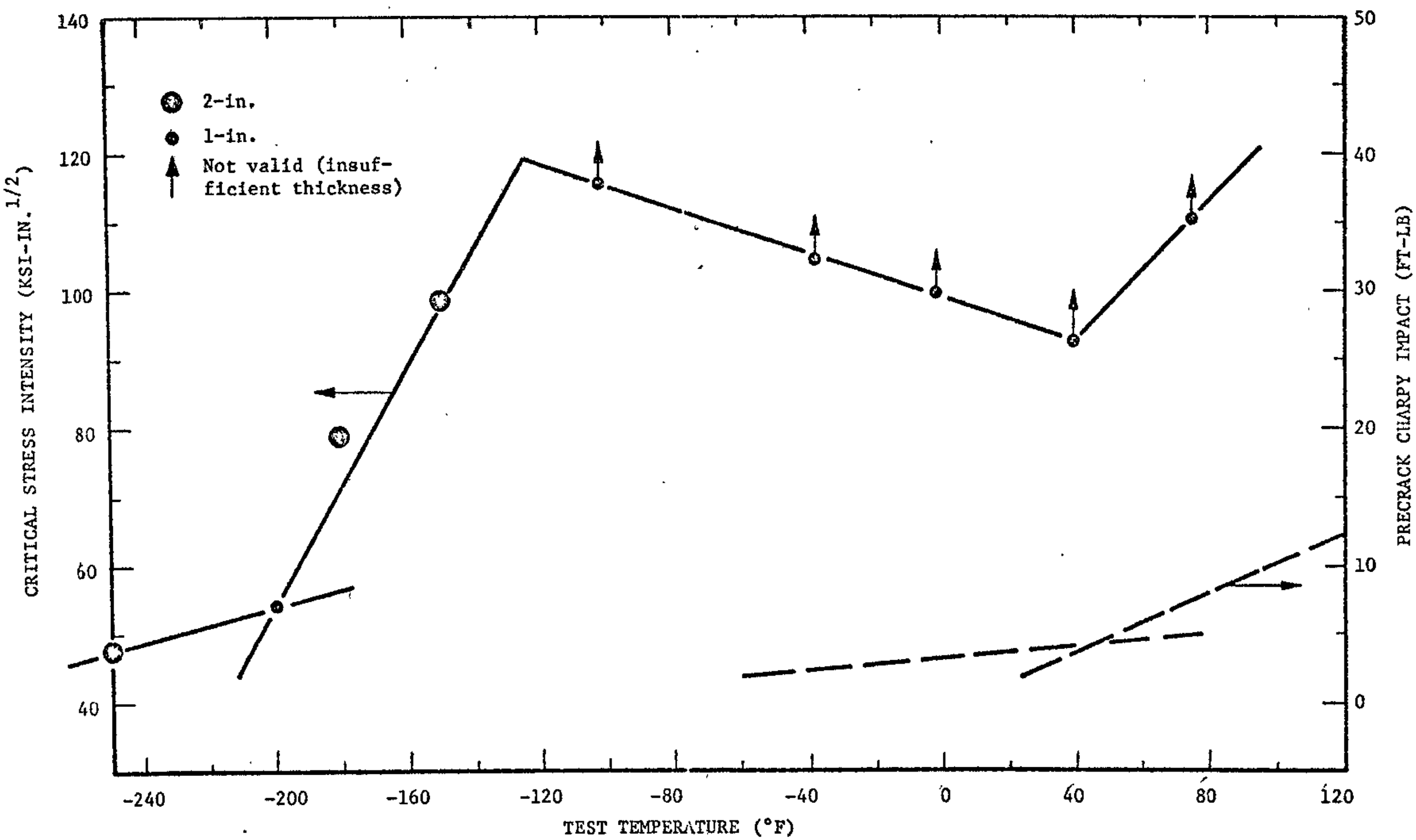


Figure 21. Static Compact Tension and Precrack Charpy Impact Test Results for Plate A(ZW).

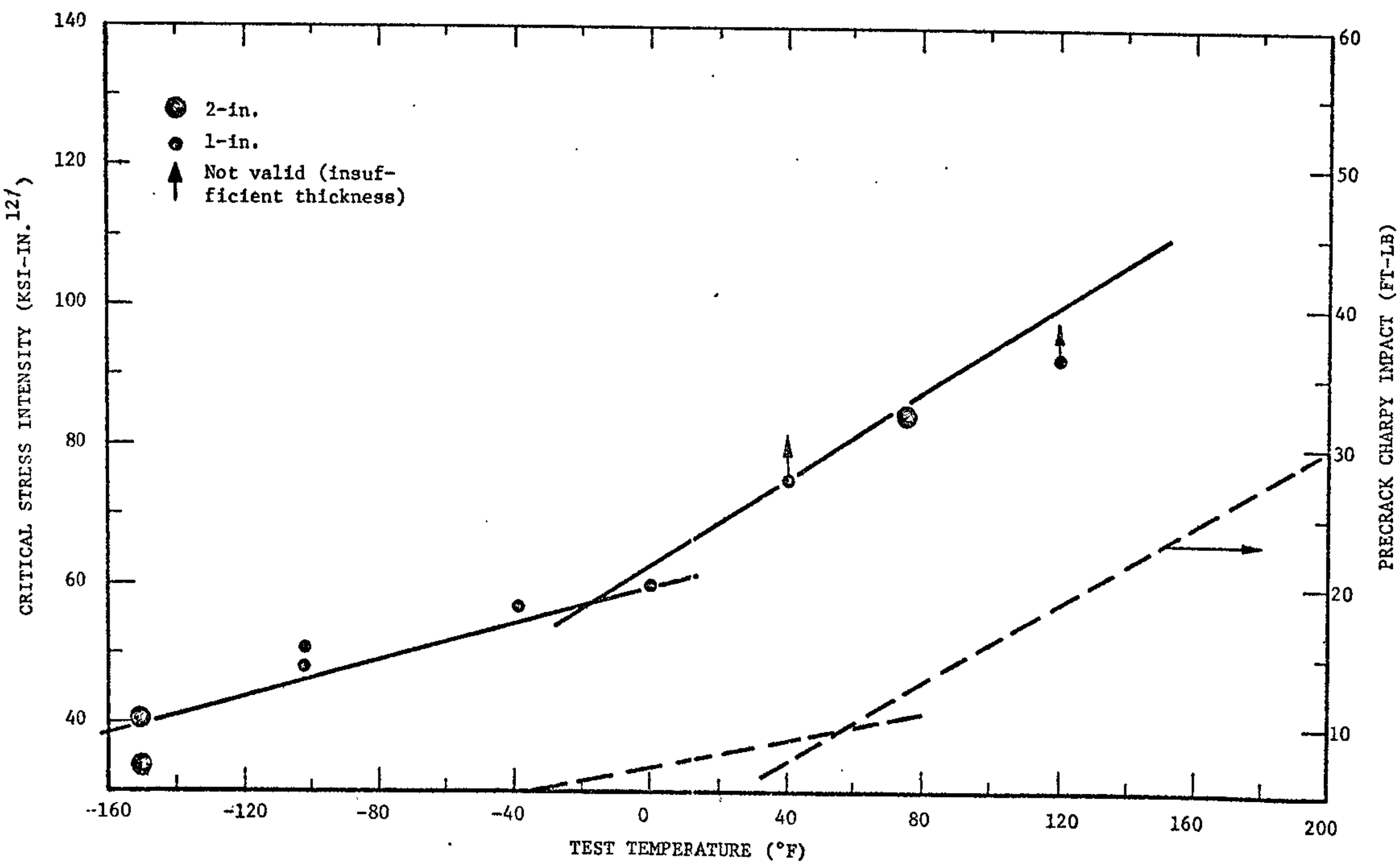


Figure 22. Static Compact Tension and Precrack Charpy Impact Test Results for Plate AL(ZY).

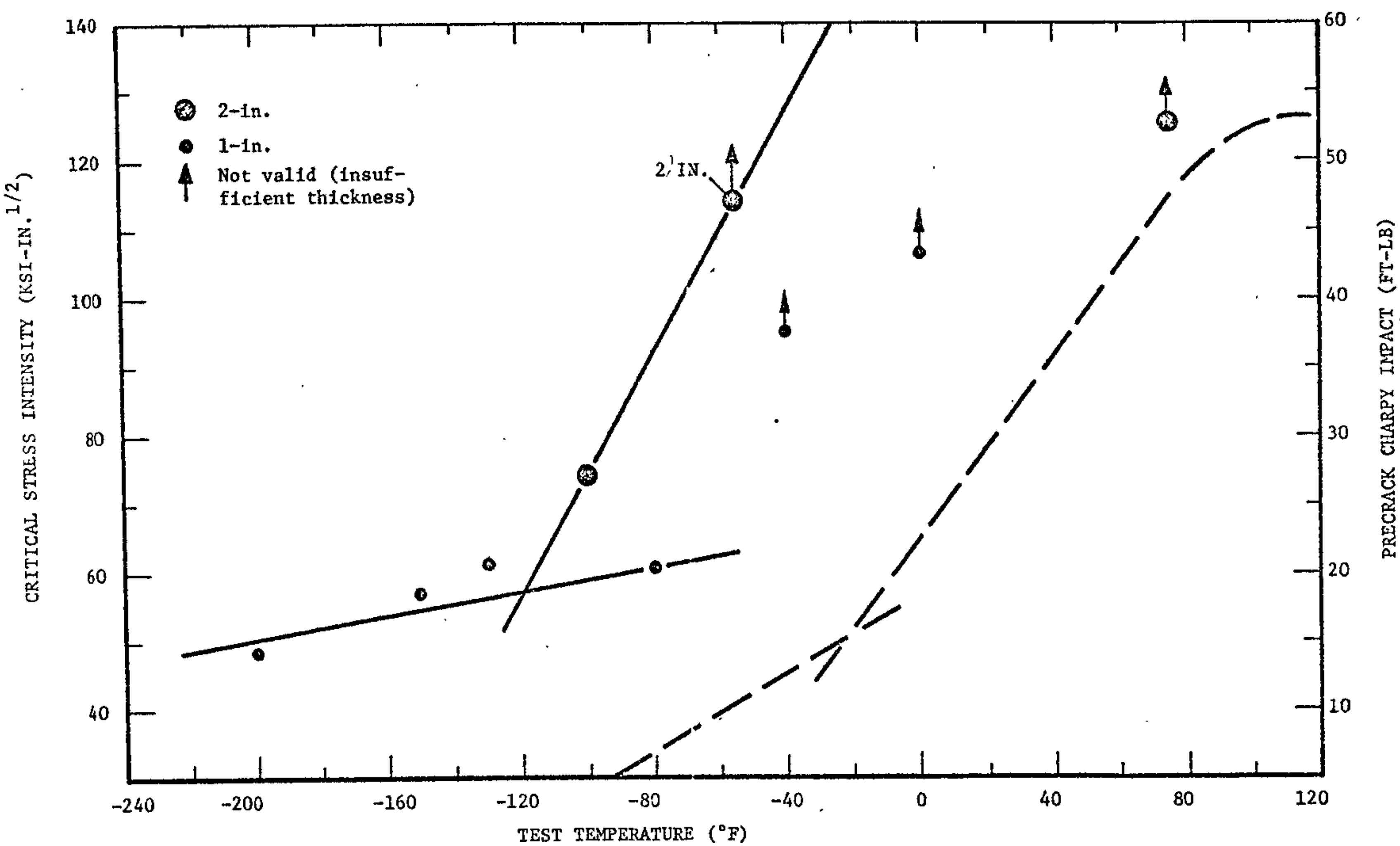


Figure 23. Static Compact Tension and Precrack Charpy Impact Test Results for Plate L(ZV).

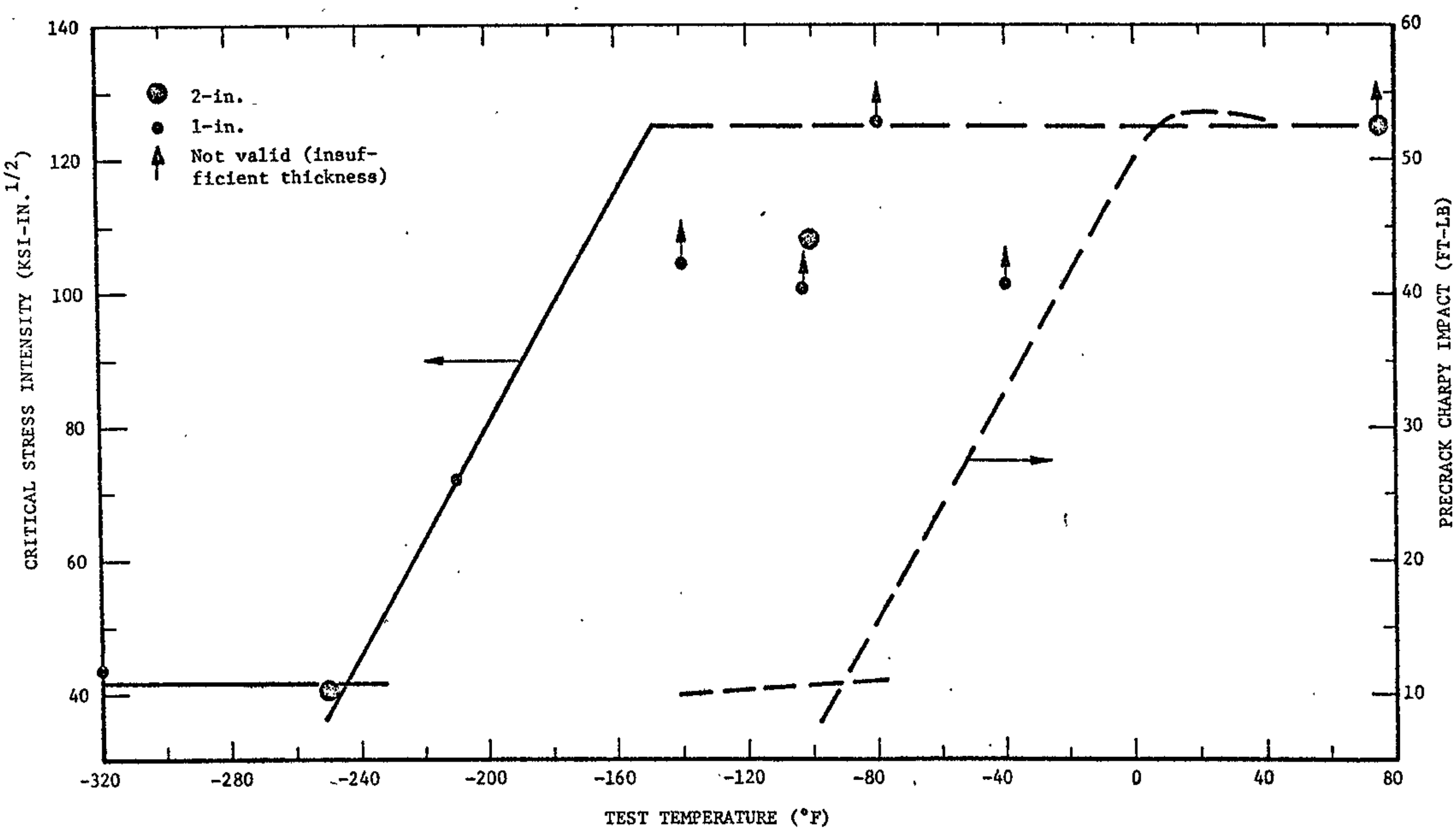


Figure 24. Static Compact Tension and Precrack Charpy Impact Test Results for Plate M(ZU).

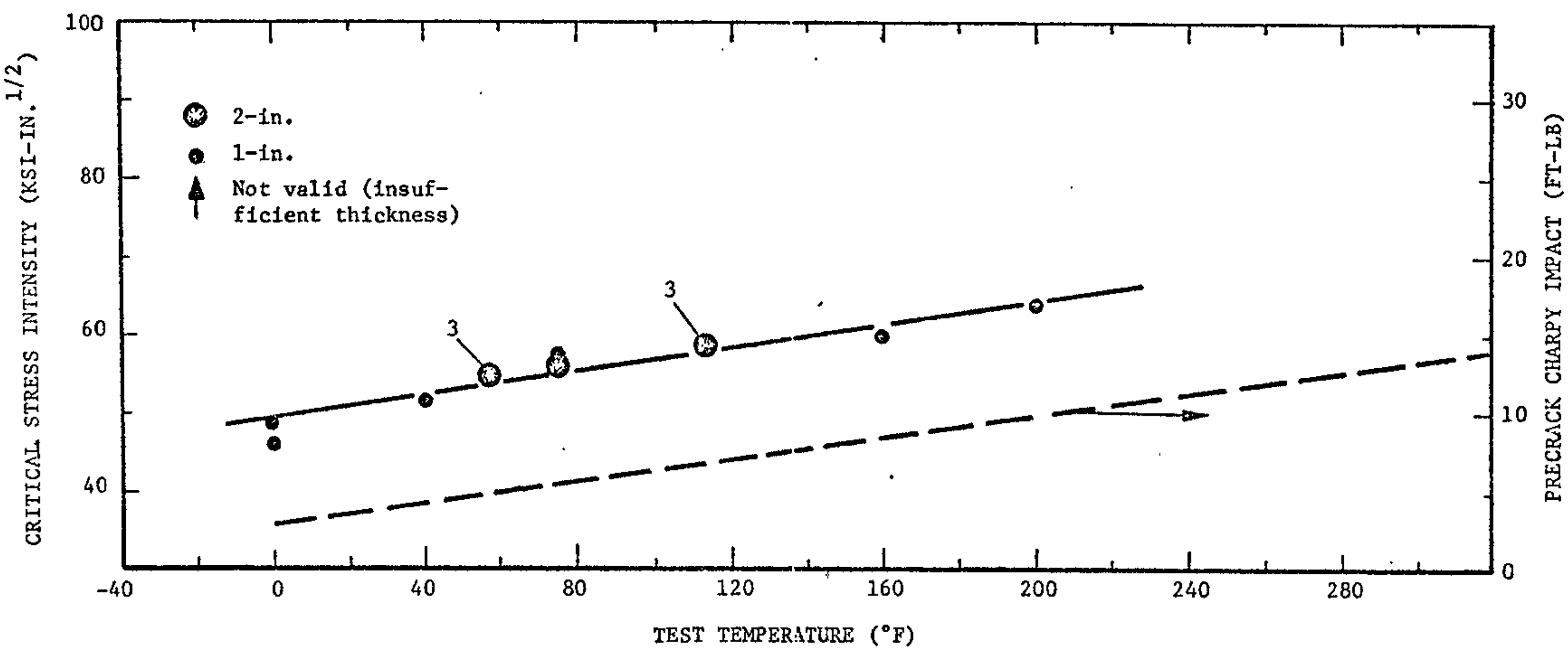


Figure 25. Static Compact Tension and Precrack Charpy Impact Test Results for Plate Q(ZZ).

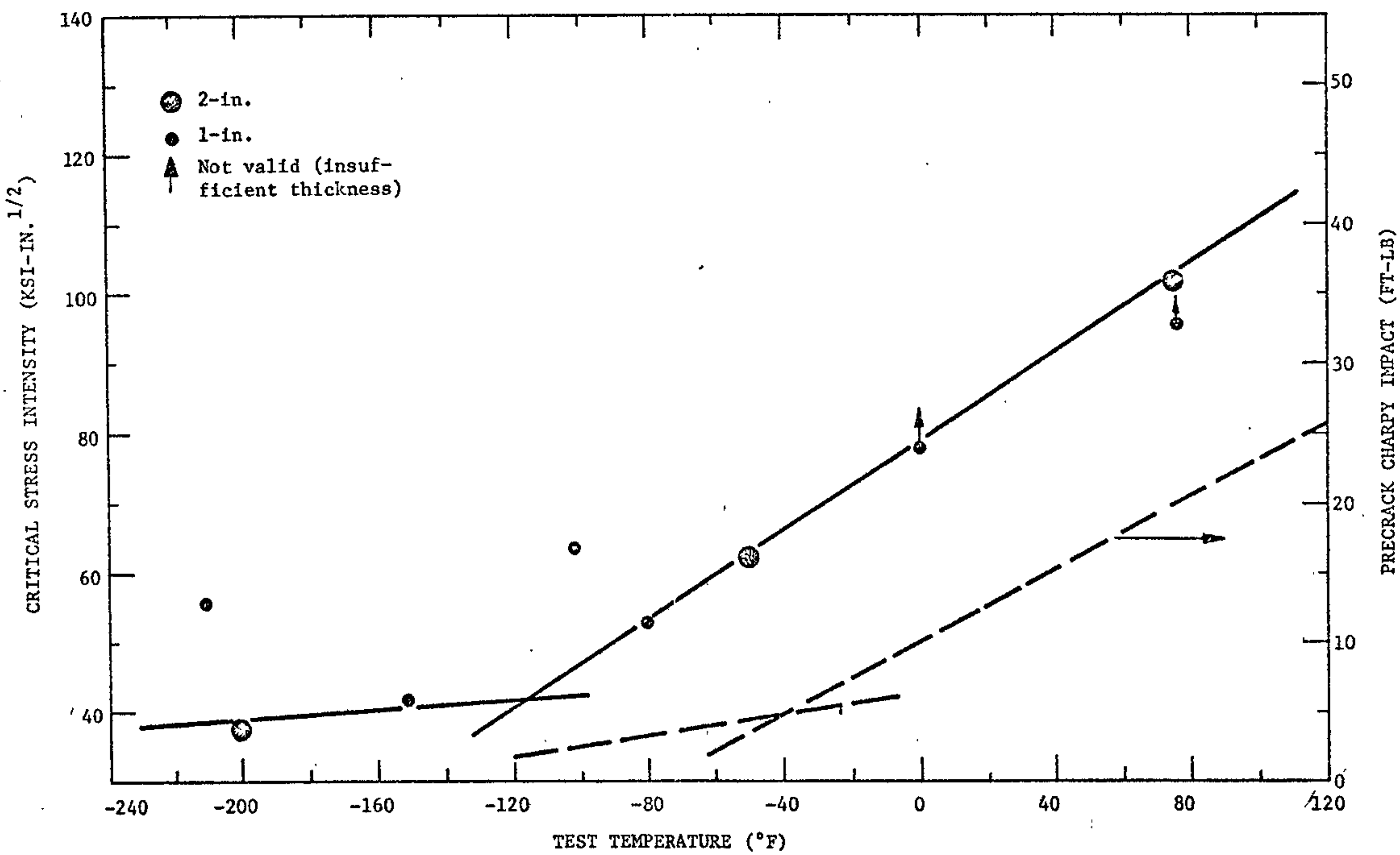


Figure 26. Static Compact Tension and Precrack Charpy Impact Test Results for Plate R(ZX).

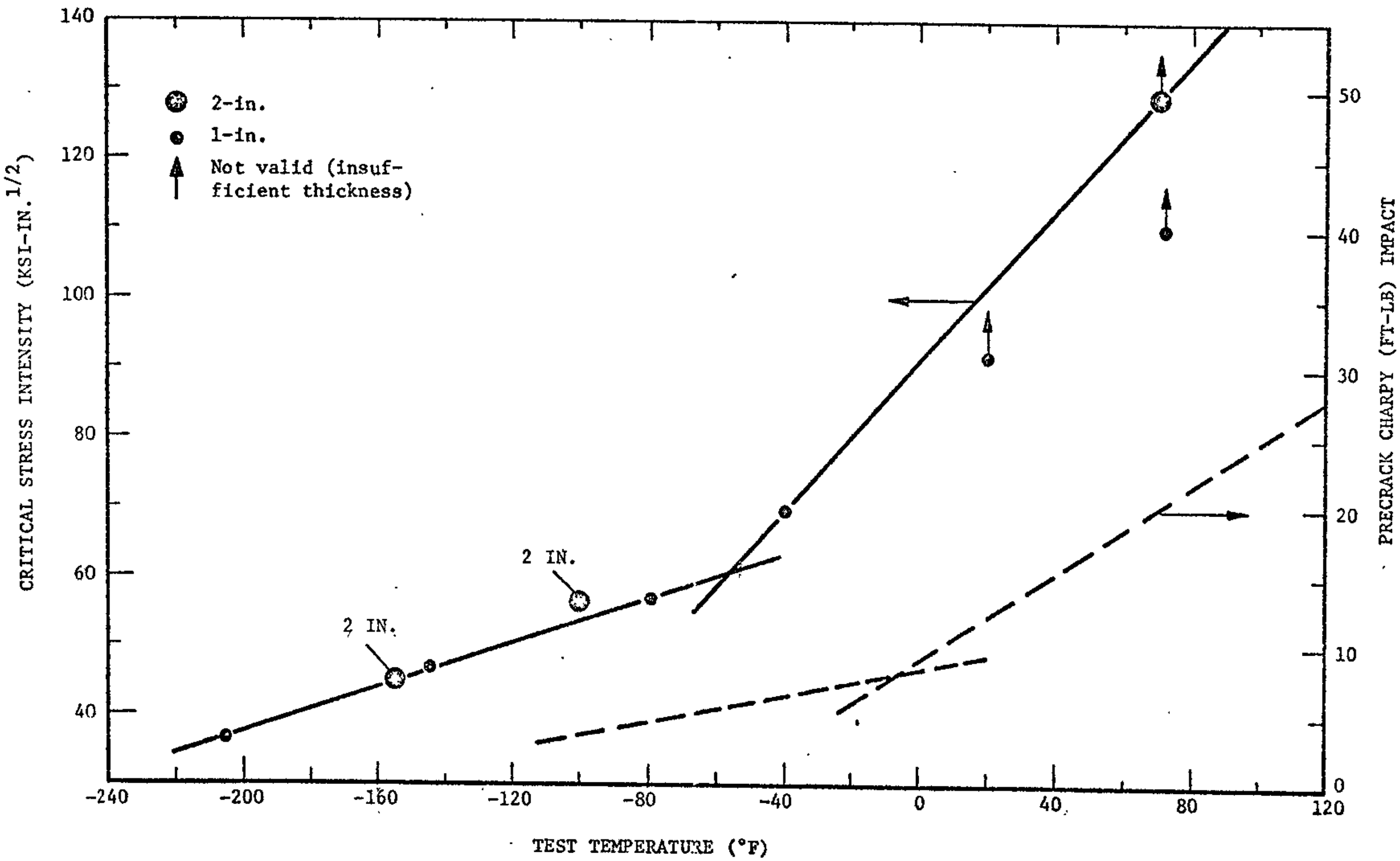


Figure 27. Static Compact Tension and Precrack Charpy Impact Test Results for Plate Z(ZT).

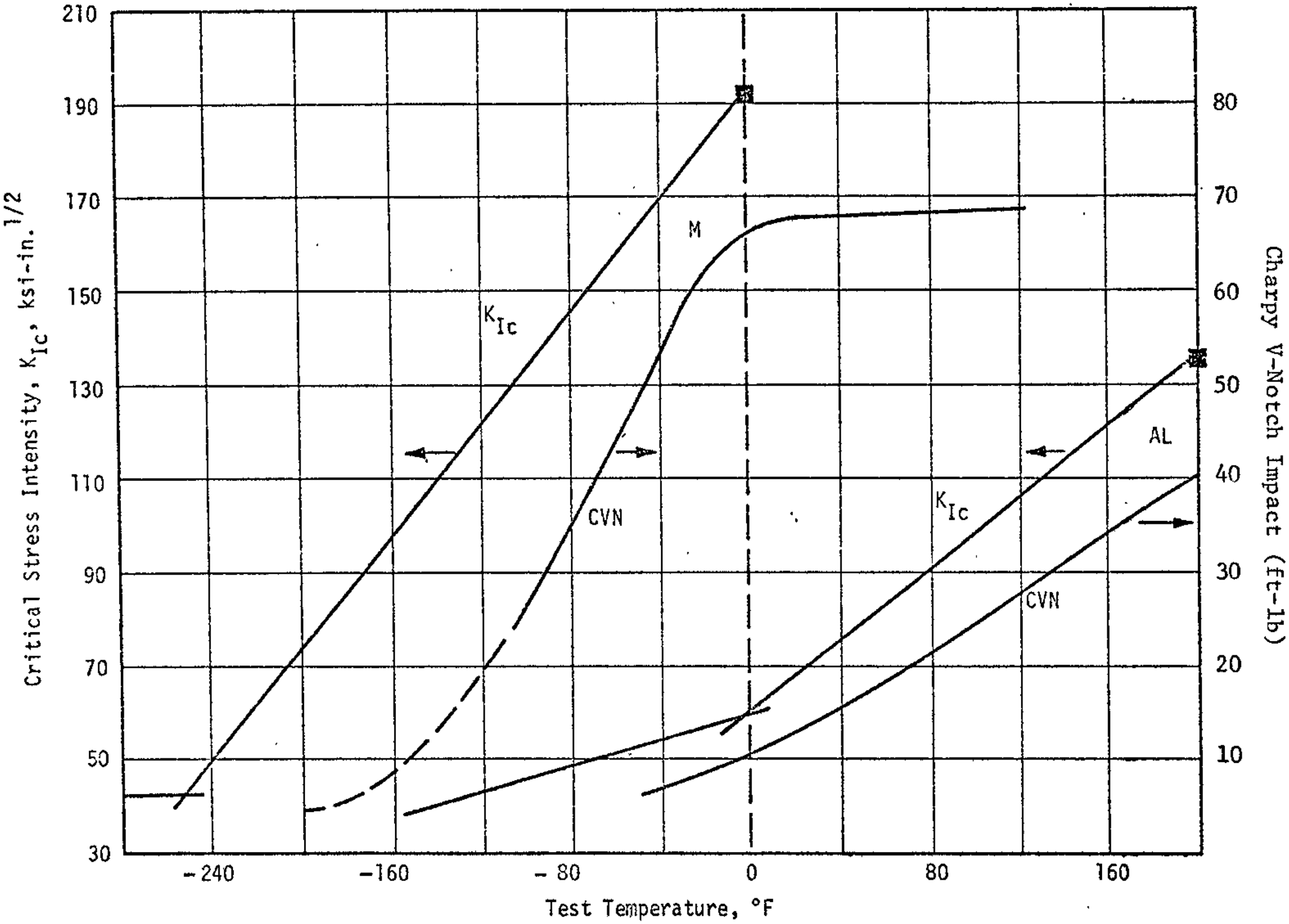


Figure 28. Limitations on the Prediction of K_{Ic} at a Specified Temperature (0°F) Based on the K_{Ic}-CVN Upper-Shelf Correlation.

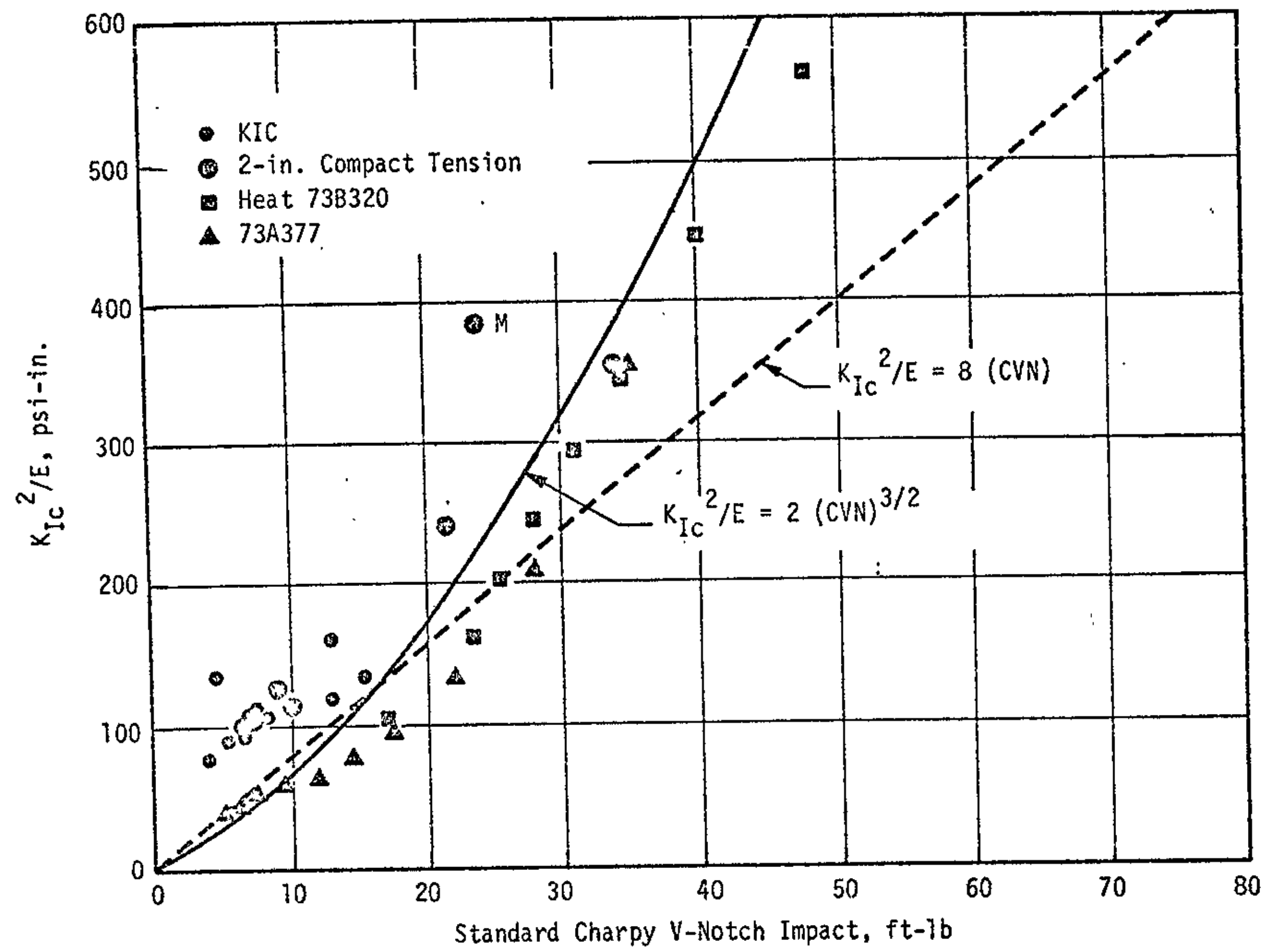


Figure 29. Transition-Temperature-Range Correlation Between Static Compact Tension K and Precrack Charpy Impact (PCI) Test Results (valid K_{Ic} data from Table 12).

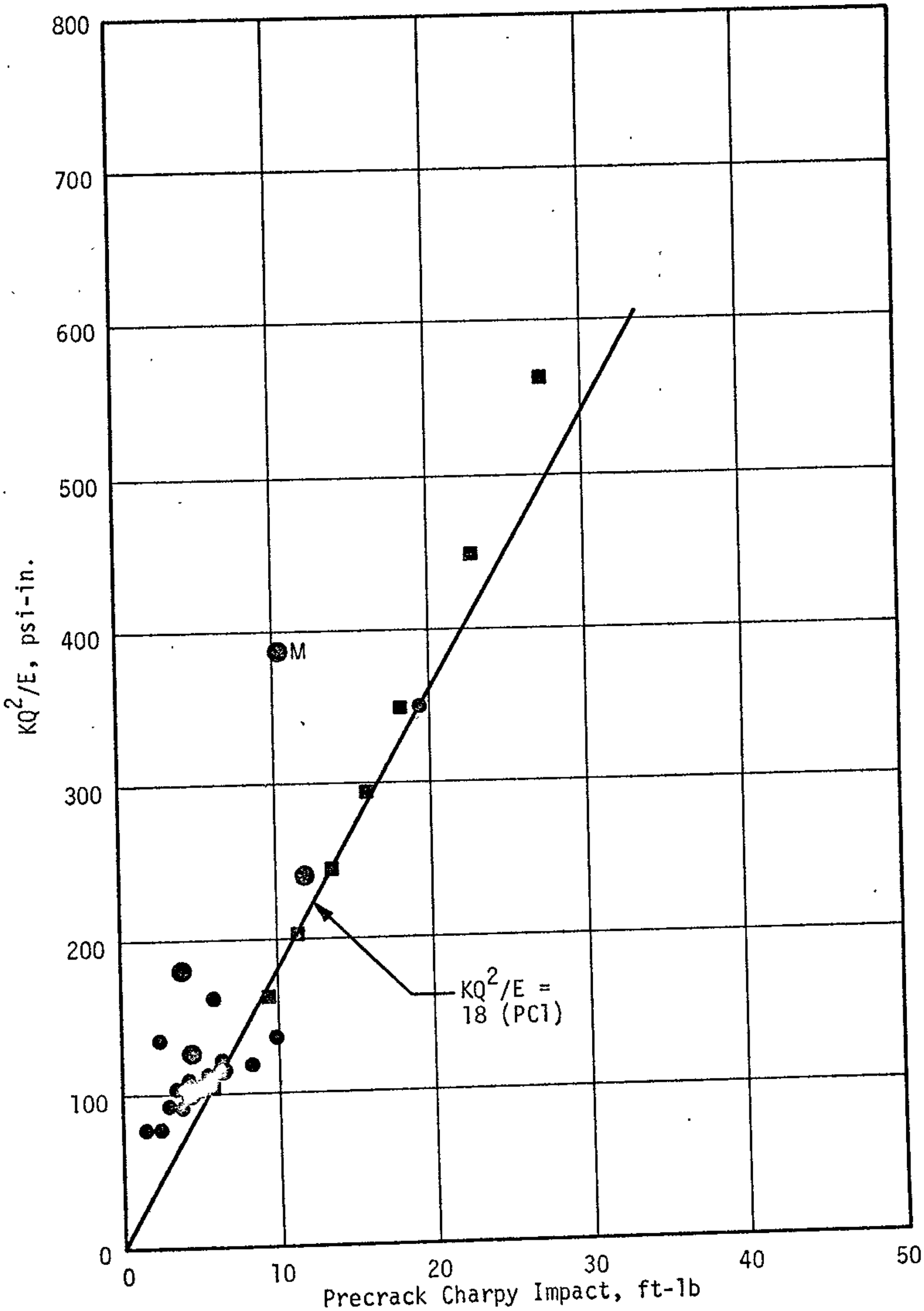


Figure 30. Transition-Temperature-Range Correlation Between Static Compact Tension K_{Ic} and Precrack Charpy Impact (PCI) Test Results (valid K_{Ic} data from Table 12).

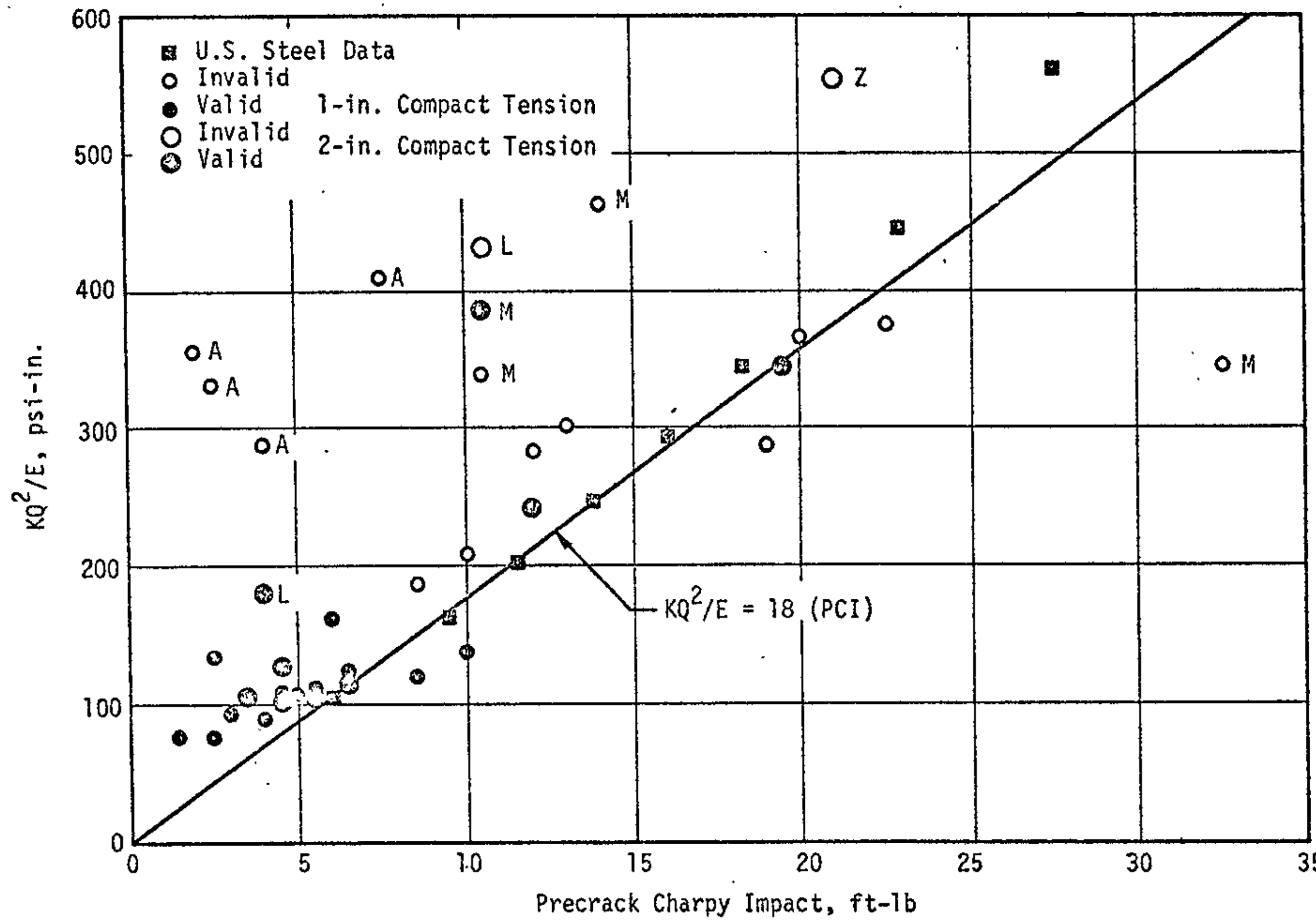


Figure 31. Transition-Temperature-Range Correlation Between Static Compact Tension K_{Ic} and Precrack Charpy Impact (PCI) Test Results (KQ and K_{Ic} data from Table 12).

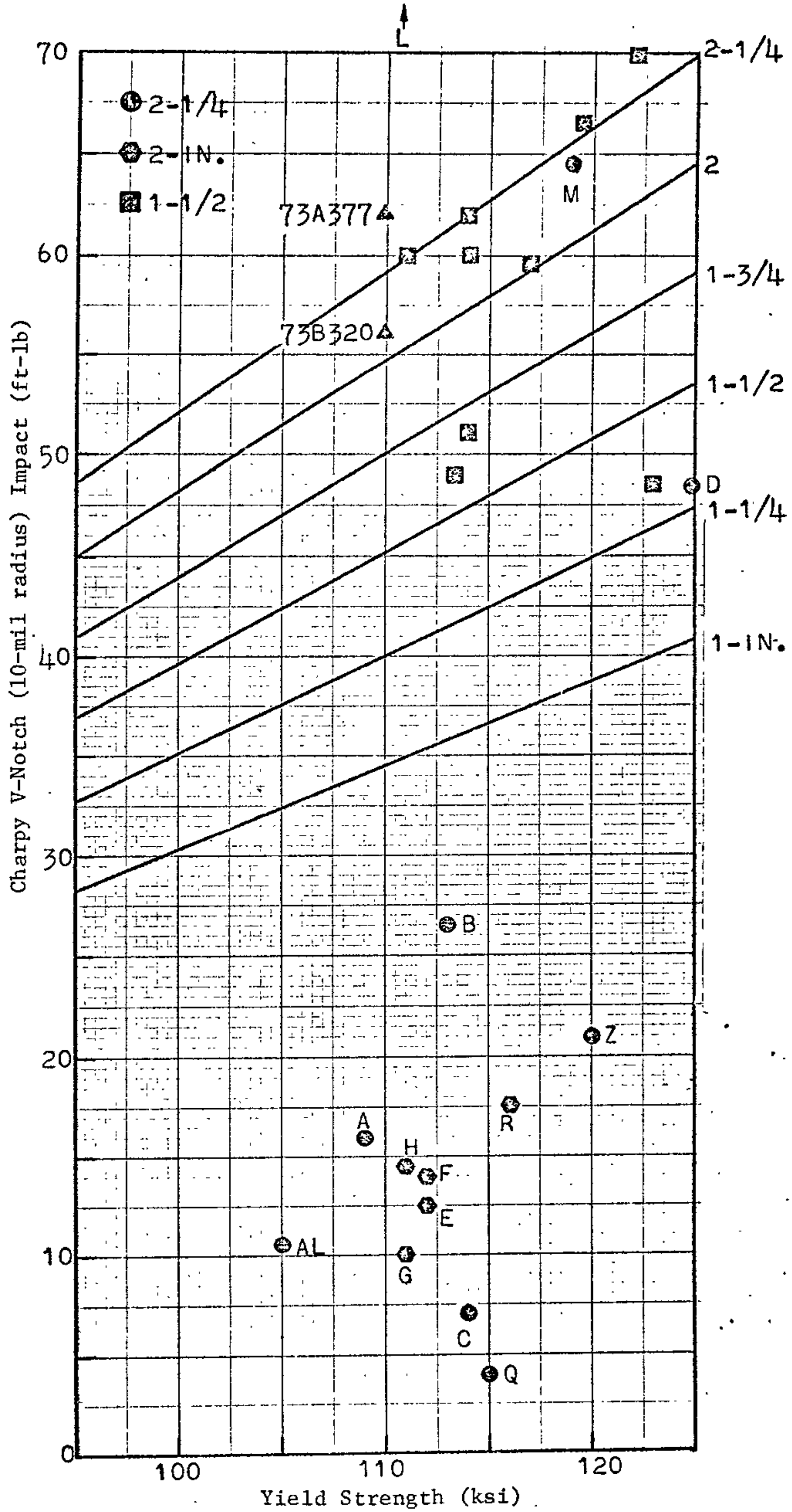


Figure 32. Charpy V-Notch Impact Requirements for Through-Thickness Yielding Based on the U.S. Steel Transition-Temperature K_{Ic}-CVN Correlation

$$FTY^2 = 2(CVN)^{3/2}\ E/B$$

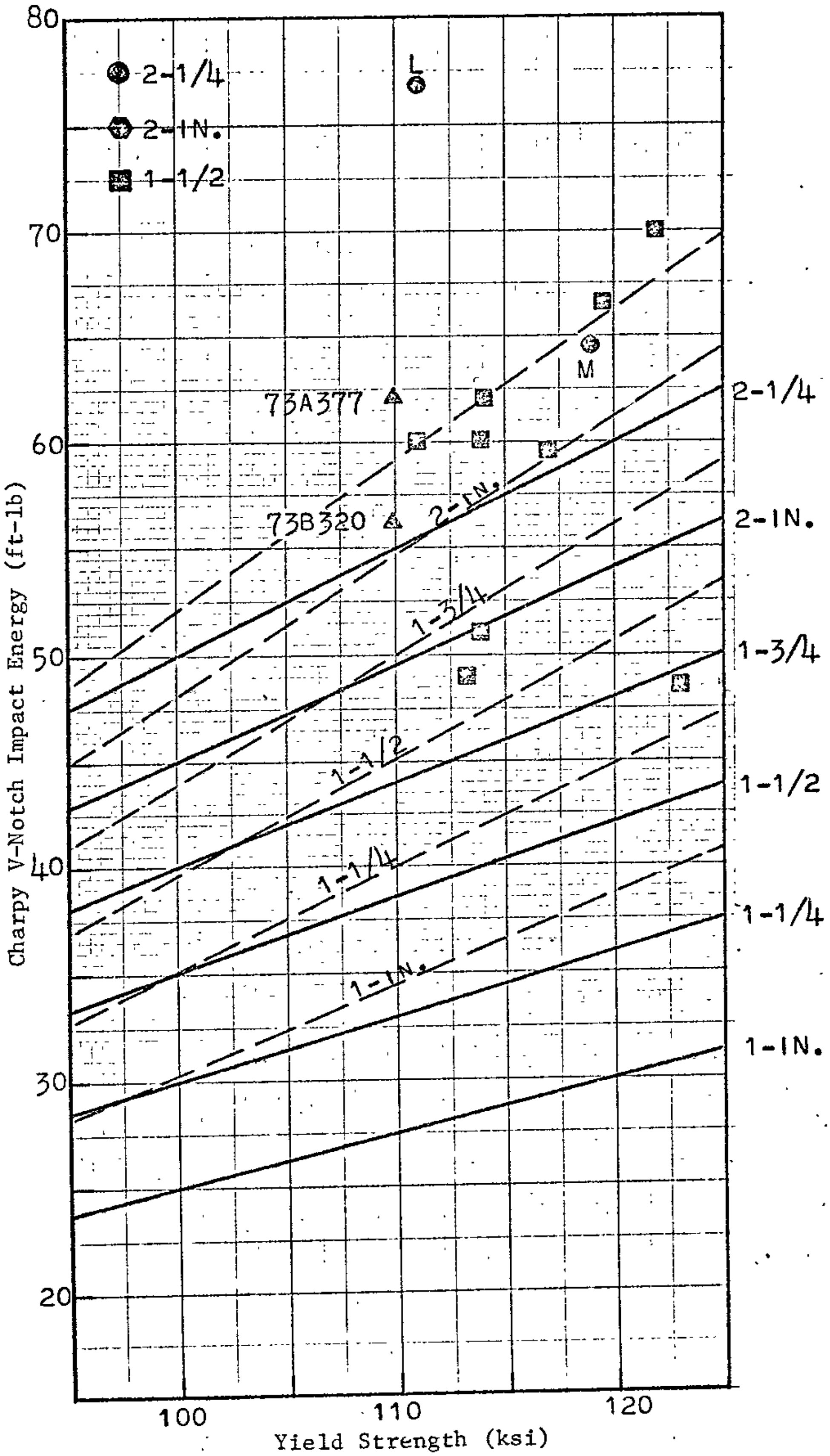


Figure 33. Charpy V-Notch Impact Requirements for Through-Thickness Yielding Based on the Upper-Shelf K_{Ic}-CVN Correlation (Dash lines from Fig. 32)

$$CVN = FTY \ (B + 0.25)/5$$

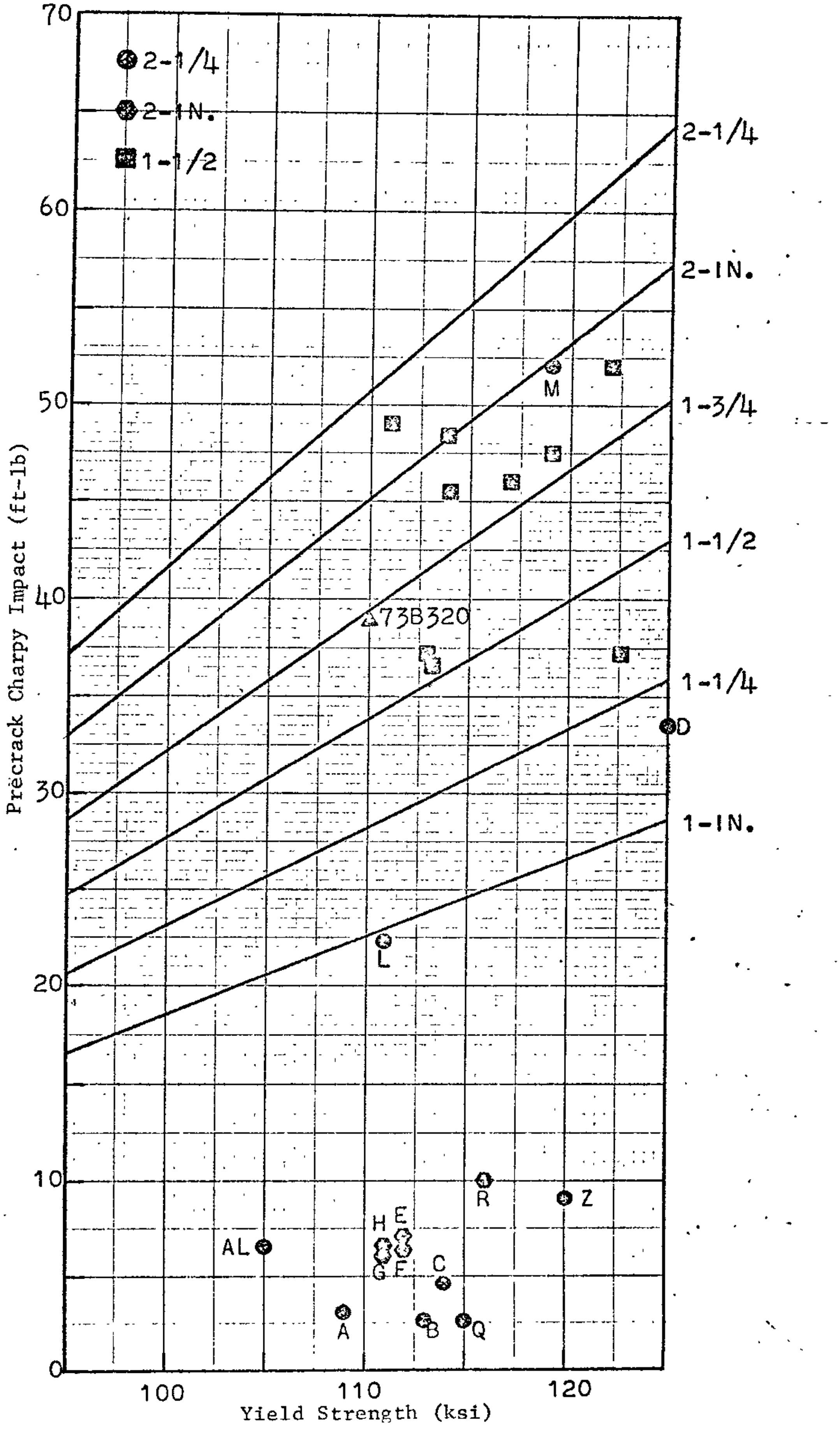


Figure 34. Charpy V-Notch Impact Requirements for Through-Thickness Yield Based on the Precrack Charpy Impact Transition-Temperature-Range K_{Ic} PCI Correlation

APPENDIX A

Charpy V-Notch (10-mil radius) and
Precrack Charpy Impact Test Results,
Tabulation of

Plate A, A517-F, 2-1/4 in., Heat B9863-2C

Precrack Charpy Impact

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-40	5A1	2.06	1
	5A2	2.10	0
	5A3	2.26	1
-20	A-1	2.01	1
	A-2	2.05	0
0	A-3	2.80	2
	A-4	2.59	2
+20	A-5	3.28	3
	A-6	3.90	3
+40	5A7	3.76	3
	5A8	3.98	4
	5A9	4.32	4
RT	5A10	7.69	8
	5A11	6.87	9
	5A12	7.01	8
+120	5A13	10.75	13
	5A14	11.60	15
	5A15	12.09	14
+160	5A16	15.8	18
	5A17	17.0	18
	5A18	17.7	21
+180	5A4	20.6	23
	5A5	18.3	23
	5A6	19.1	21
+210	5A19	23.8	26
	5A20	29.2	31
	5A21	29.7	30

Charpy V-Notch

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-40	6A1	13.20	10
	6A2	14.55	11
	6A3	13.28	8
0	6A4	15.20	9
	6A5	15.73	11
	6A6	16.42	11
40	6A7	17.29	11
	6A8	20.19	14
	6A9	15.73	10
+74	6A10	19.40	13
	6A11	18.58	14
	6A12	16.68	12

Plate A, A517-F, 2-1/4 in., Heat B9863-2C (Cont.)

Charpy V-Notch (cont.)

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
+120	6A13	21.40	21
	6A14	25.36	20
	6A15	26.35	24
+160	6A16	30.57	26
	6A17	30.48	25
	6A18	27.19	24
+210	6A19	37.93	32
	6A20	39.06	35
	6A21	42.53	36

Plate AL, A517H, 2-1/4 in., Heat A4071-6

Precrack Charpy Impact

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
+80	5AL1	2.61	0
-40	5AL2	4.82	2.5
0	5AL9	6.33	3.5
+20	5AL3	8.30	7.0
	AL-1	7.05	6.0
-40	AL-2	8.60	9.5
	AL-3	8.72	7.5
+60	AL-4	9.04	10.0
	AL-5	10.50	10.5
+74	5AL4	13.0	12.5
	5AL8	14.1	12.5
+120	5AL5	19.0	17.0
+160	5AL7	24.2	22.5
	AL-6	20.85	21.5
+210	5AL6	32.6	32.0

Charpy V-Notch

-40	4AL1	6.95	2.5
0	4AL2	10.5	7
+20	4AL3	11.9	8
	4AL4	10.4	6
	4AL5	13.1	9
+74	4AL6	20.85	16.5
	4AL10	22.5	18
+120	4AL7	24.7	20.5
	4AL9	31.1	26.5
+210	4AL8	41.8	36.5

Plate L, A517F, 2-1/4 in., Heat 97L168-06W2

Precrack Charpy Impact

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-80	5L1	7.2	6
	5L10	6.8	4.5
-60	L-1	10.2	10.5
	L-2	9.4	8
-40	5L2	12.4	10
	L-3	13.9	12.5
	L-4	14.0	13
-20	L-5	15.5	15
	L-6	18.6	17
0	5L7	26.3	24.5
	5L8	24.9	20
+20	5L3	23.2	19
+40	L-7	36.9	36
	L-8	42.6	37
+73	5L4	44.4	39.5
	5L9	48.4	39.5
+120	5L5	52.8	45
+210	5L6	52.6	45

Charpy V-Notch

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-80	4L9	10.9	7.5
	4L10	8.8	5.5
-40	4L1	39.8	29
0	4L2	72.3	50
+20	4L3	79.1	48
	4L4	65.5	44
	4L5	70.5	45
+73	4L6	79.1	51
+120	4L7	78.8	51.5
+210	4L8	74.9	53

Plate M, A514-F, 2-1/4 in., Heat 92L088-10W2

Precrack Charpy Impact

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-100	5M9	9.4	7.5
	M-1	11.6	10
	M-2	11.8	12
-80	5M1	14.8	13.5
	5M10	13.4	13.0
-60	M-3	23.2	20.5
	M-4	20.4	21
-40	5M2	36.2	28.5
	5M9	29.4	23
-20	M-5	36.3	34
	M-6	42.4	37.5
0	5M8	51.0	41.5
+20	5M3	53.2	41.5
+74	5M4	51.3	42
+120	5M5	52.3	45
+210	5M6	49.4	42.5

Charpy V-Notch

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-100	4M10	24.1	17.5
-80	4M9	32.2	23
-40	4M1	51.3	34
0	4M2	64.7	44
+20	4M3	66.7	47
	4M4	64.5	46.5
	4M5	65.8	47.5
+74	4M6	66.7	41.5
+120	4M7	66.7	48.5
+210	4M8	64.8	46

PRECRACK CHARPY IMPACT TEST
HEAT C4913 SLAB 4

Spec. No.	Temp (°F)	Location	Degree	ft-lb
2C13	0	Midthick.	161.9	2.2
2C16			160.7	2.6
2A19		Surface	157.3	4.0
2B14			158.9	3.3
1C8	76	Midthick.	153.4	5.8
2C7			154.2	5.5
1A1		Surface	151.0	7.1
1B7			150.9	7.1
2A1			152.0	6.6
2B7			150.6	7.3
1C11	120	Midthick.	151.4	6.9
2C10			151.9	6.6
1A4		Surface	147.7	9.0
1A19			149.6	7.9
1B10			149.9	7.7
1B19			151.0	7.1
1C18	160	Midthick.	148.3	8.6
1C19			150.1	7.6
2A11		Surface	146.9	9.5
2A12			146.9	9.5
2B10			148.0	8.8
1C9	210	Midthick.	147.0	9.5
2C8			145.6	10.3
1A2		Surface	144.0	11.4
1B8			144.0	11.4
2A2			143.7	11.6
2B8			144.8	10.8
1C10	300	Midthick.	139.3	14.6
1A3		Surface	138.0	15.6
1B9			139.6	14.4
2C11	360	Midthick.	137.3	16.1
2C12			139.0	14.9
2A17		Surface	135.5	17.6
2A18			137.2	16.2
2B12			138.2	15.5

STANDARD CHARPY V-NOTCH IMPACT TEST
HEAT C4913 SLAB 4

Spec. No.	Temp (°F)	Location	Degree	ft-lb
1C13	-40	Midthick.	160.9	2.6
2C19			159.6	3.1
2A16		Surface	157.7	3.9
2B18			158.6	3.5
1A15			156.1	4.6
1B17			158.7	3.5
1C2	0	Midthick.	156.4	4.4
2C2			158.5	3.5
1B2		Surface	154.0	5.6
2B2			157.0	4.2
3B2			154.2	5.4
1C1	76	Midthick.	150.5	7.4
2C1			149.8	7.8
1B1		Surface	145.7	10.2
2B1			147.8	9.0
3B1			143.4	11.8
1C6	120	Midthick.	144.3	11.2
2C5			146.8	9.6
1B5		Surface	142.8	12.2
2B5			143.2	11.9
1C7	210	Midthick.	135.9	17.2
2C6			137.4	16.1
1B6		Surface	134.1	18.7
2B6			132.2	20.2
3B8			131.8	20.6
1C12	300	Midthick.	130.6	21.6
2C9			128.9	23.0
1A6		Surface	128.9	23.0
2A3			127.0	24.8
1B11			129.5	22.6
2B9			130.9	21.4
1C14	360	Midthick.	127.4	24.4
2C17			123.7	27.8
1A14		Surface	125.4	26.2
1A18			124.4	27.2

Plate R, A514-H, 2-in., Heat 07619-03W1

Precrack Charpy Impact

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-100	5R9	2.60	0
-80	5R1	2.92	0
-60	R-1	4.11	2.5
	R-2	4.49	3.5
-40	5R2	4.42	2
	R-3	5.73	5
	R-4	5.38	4
-20	R-5	7.22	7
	R-6	6.30	6
0	5R7	9.77	8
	5R8	10.2	8.5
+20	5R3	12.0	11.5
+73	5R4	17.8	16.5
+120	5R5	26.0	23.5
+210	5R6	35.5	35

Charpy V-Notch

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-80	4R9	6.23	4.5
-40	4R1	10.0	9.5
0	4R2	19.05	13.5
+20	4R10	24.3	18
	4R3	21.8	18
	4R4	22.8	16
	4R5	16.9	12.5
+73	4R6	33.9	25.5
+120	4R7	43.5	34.5
+210	4R8	56.4	47

Plate Z, A517-H, 2-1/4 in., Heat B9093-4B

Precrack Charpy Impact

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-100	5Z8	3.41	1.5
-80	5Z1	4.32	1.5
-60	Z-1	4.43	1
	Z-2	5.42	2.5
-40	5Z2	6.42	4
	Z-3	5.92	2.5
-20	5Z10	6.98	5.5
	Z-4	7.18	6
0	5Z9	9.67	7
	Z-5	9.67	7
+20	5Z3	13.2	10
	5Z7	11.05	9
+40	Z-6	13.6	11.5
	Z-7	13.1	9.5
+74	5Z4	20.35	17
	Z-8	19.1	15
+120	5Z5	29.8	24
+210	5Z6	41.3	33.5

Charpy V-Notch

Test (°F)	Specimen No.	Energy (ft-lb)	Lat Expans (mils)
-100	4Z10	7.55	3.5
-80	4Z9	8.13	3.5
-40	4Z1	10.9	6.5
0	4Z2	22.5	15.5
+20	4Z3	25.3	17.5
	4Z4	23.6	18
	4Z5	28.8	19
+74	4Z6	36.1	20.5
+120	4Z7	45.6	32.5
+210	4Z8	55.0	41.5

APPENDIX B

SUMMARY OF U.S. STEEL DATA
ON TWO HEATS OF ASTM A517-F
PLATE.

FRACTURE BEHAVIOR OF U.S. STEEL HEATS

		U.S.S. 73B320	U.S.S. Heat 73A377			
		Ref. (2)	Ref. (3)	(4)	(5)	(8)
Yield Strength	(ksi)	110	118	118	121	110
Ultimate	(ksi)	122	129	129	134	121
Charpy V-Notch						
@ 80°F	(ft-lb)	56	47	57	50	62
15 ft-lb	(°F)	-170		-160	-90	
15 mils	(°F)	-140			-60	
Precrack Charpy						
impact	(°F)	-120			-65	
slow bend	(°F)	-170			-	
NDT (Drop-Wgt.)	(°F)	-	-40		-30	
K_{Ic} (Slow Bend)	(°F)	-120	-120			
@ 80°F	(ksi-in.$^{1/2}$)	82[a]	76[a]	80[a]		170
K_{Id} (Dynamic)	(ksi-in.$^{1/2}$)		45[a]			
CVN/FTY	(ft-lb/ksi)		0.40	0.40	0.41	0.56
$(KQ/FTY)^2$	(in.)		2.07	2.07	1.97	2.39

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(a) tested at minus 100°F

(2) J. M. Barsom and S. T. Rolfe, "K_{Ic} Transition-Temperature Behavior of A517-F Steel", AD 846 124L, 29 Nov. 1968, and ENGINEERING FRACTURE MECHANICS, 1971, Vol. 2, pp. 341-357.

(3) A. K. Shoemaker and S. T. Rolfe, "The Static and Dynamic Low-Temperature Crack Toughness Performance of Seven Structural Steels", AD 846-126L, 29 Nov. 1968, and ENGINEERING FRACTURE MECHANICS, 1971, Vol. 2, pp. 319-339.

(4) J. M. Barsom and S. T. Rolfe, "Correlations Between K_{Ic} and Charpy V-Notch Test Results in the Transition-Temperature Range", IMPACT TESTING OF METALS, ASTM STP 466, 1970, pp. 281-302.

(5) J. H. Gross, "Effect of Strength and Thickness on Notch Ductility", IMPACT TESTING OF METALS, ASTM STP-466, 1970, pp. 21-52.

(8) S. T. Rolfe and S. R. Novak "Slow-Bend K_{Ic} Testing of Medium-Strength High Toughness Steels" AD 817-373L, August 1967. Also ASTM STP 463, American Society for Testing and Materials, 1970, pp. 124-159.

HEATS USED IN U.S. STEEL INVESTIGATIONS

Source (Ref)	Heat No.	C	Mn	P	S	Si	Ni	Cu	Cr	Mo	V	B	FTY	FTU	Elong.	R.A.	Thick.	CVN @80°F
2	73B320	.17 .17	.88 .89	.011 .015	.016 .015	.22 .19	.84 .84	.28 .30	.52 .52	.45 .42	.04 .04	.003[b] .003	110/109 110/104	122/120 121/118	18.8/19.0 20.0/22.0	62/61[c] 63/63	1-in. 2-in.	56
3	(73A377)[a]	.16 .17	.79 .78	.010 .012	.016 .017	.23 .23	.87 .88	.26 .26	.53 .56	.43 .42	.04 .036	.003 .0033	118	129	19.0	65.4		47
4	(73A377)[a]	.17	.78	.012	.017	.23	.88	.26	.56	.42	.036	.0033	118	129	19	65		47
5	73A377	.16 .17	.79 .78	.010 .012	.016 .017	.23 .23	.87 .88	.26 .26	.53 .56	.43 .42	.04 .036	.003 .0033	121/121	134/134	19/17	63/50		50
8	(73A377)[a]	.16	.79	.010	.016	.23	.87	.26	.53	.43		.003	110	121	20	66	2-in.	62

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(a) parenthesis indicates heat not stated in reference (assumed from chemistry).

(b) where two values are given, first is ladle, second is check.

(c) where two values are given, first is longitudinal, second is transverse; single value is longitudinal.